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**Lewandowski et al.**

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(54) **ULTRA-ACCELERATED NATURAL  
SUNLIGHT EXPOSURE TESTING  
FACILITIES**

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(\*) Notice: Subject to any disclaimer, the term of this  
patent is extended or adjusted under 35  
U.S.C. 154(b) by 0 days.

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(21) Appl. No.: **10/423,314**

(22) Filed: **Apr. 25, 2003**

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US 2003/0200824 A1 Oct. 30, 2003

**Related U.S. Application Data**

(60) Division of application No. 09/521,731, filed on Mar. 9,  
2002, now Pat. No. 6,604,436, which is a continuation-in-  
part of application No. 09/006,746, filed on Jan. 13, 1998,  
now Pat. No. 6,073,500.

(51) **Int. Cl.**<sup>7</sup> ..... **G01N 17/00**

(52) **U.S. Cl.** ..... **73/865.6; 359/726; 359/853**

(58) **Field of Search** ..... **73/865.6; 374/57;**  
**359/726-727, 850-853; 126/573, 684-685,**  
**692**

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(74) *Attorney, Agent, or Firm*—Paul J. White

(57) **ABSTRACT**

A multi-faceted concentrator apparatus for providing ultra-  
accelerated natural sunlight exposure testing for sample  
materials under controlled weathering conditions compris-  
ing: facets that receive incident natural sunlight, transmits  
VIS/NIR and reflects UV/VIS onto a secondary reflector that  
delivers a uniform flux of UV/VIS onto a sample exposure  
plane located near a center of a facet array in a chamber that  
provide concurrent levels of temperature and/or relative  
humidity at high levels of up to 100× of natural sunlight that  
allow sample materials to be subjected to accelerated irra-  
diance exposure factors for a significant period of time of  
about 3 to 10 days to provide a corresponding time of about  
at least a years worth representative weathering of sample  
materials.

**2 Claims, 13 Drawing Sheets**

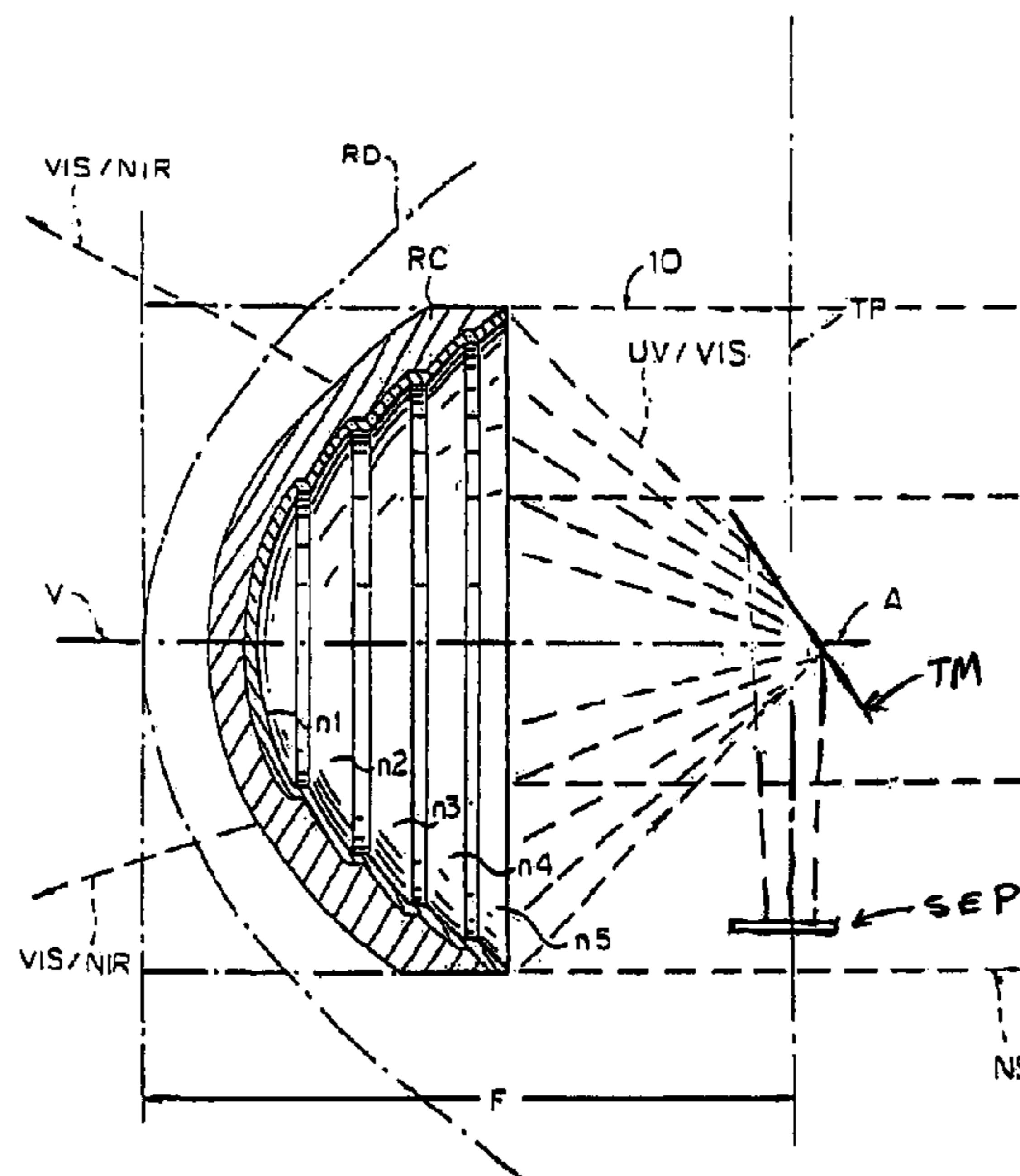


FIG. 1

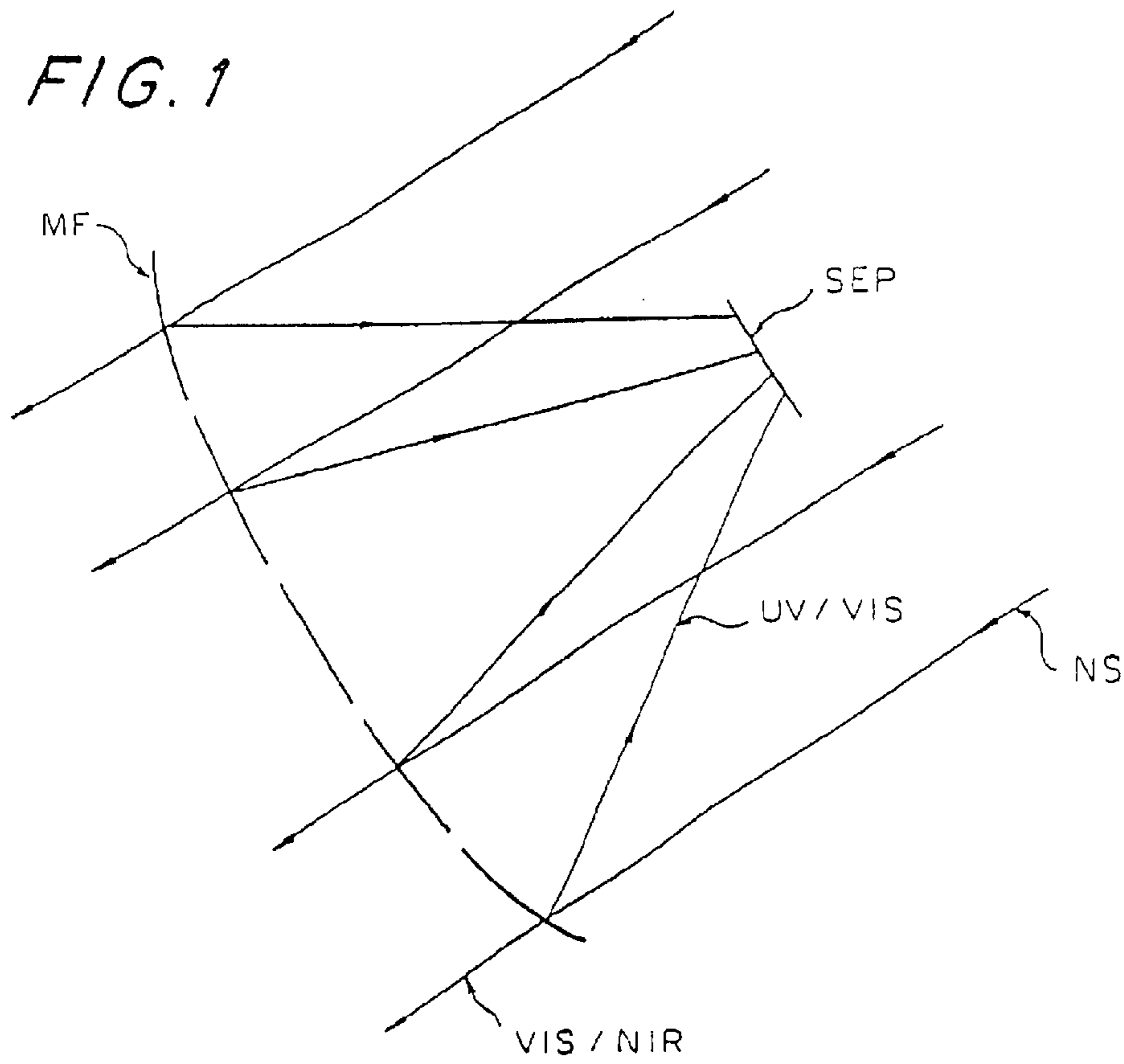


FIG. 2

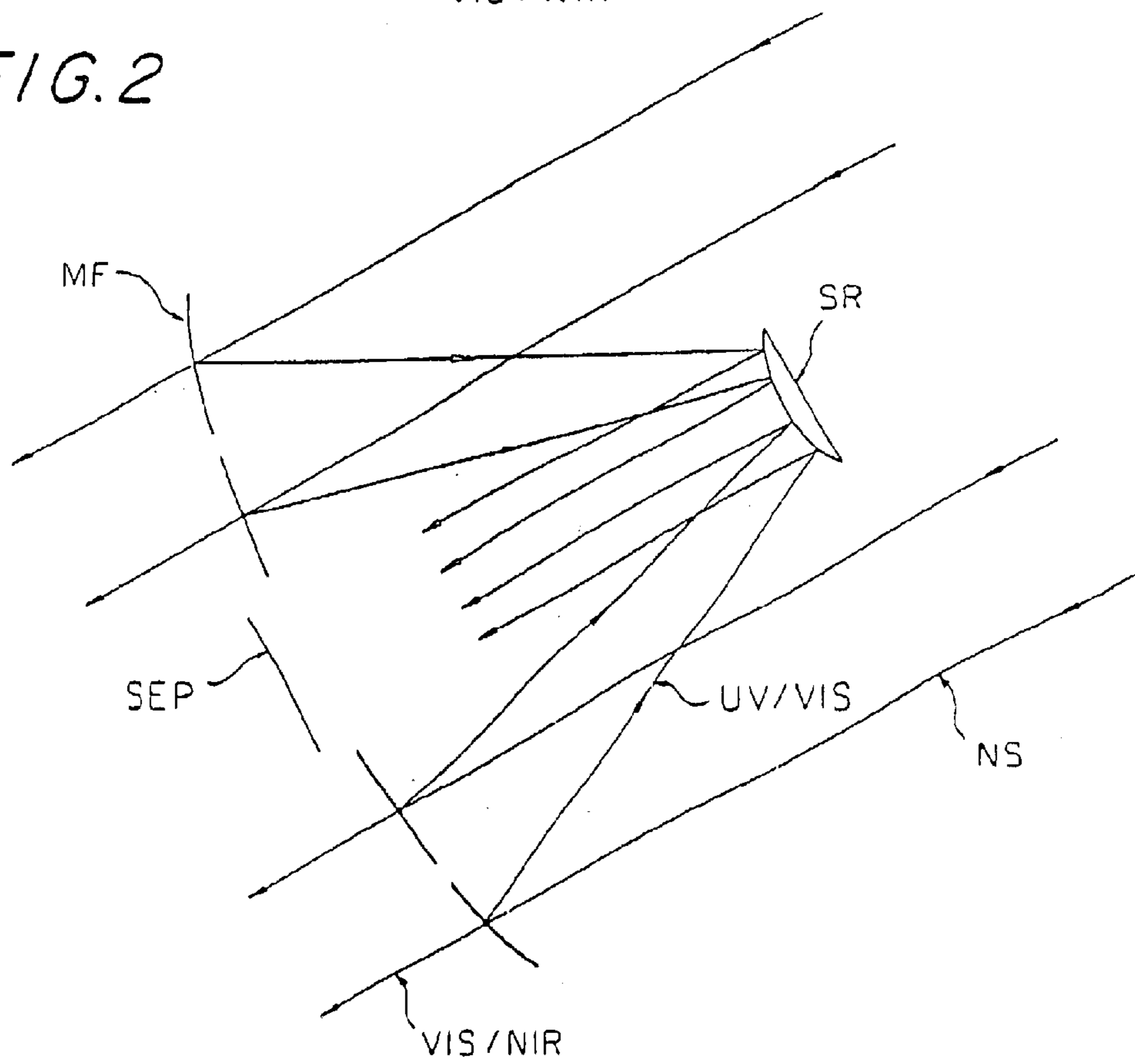


FIG. 3

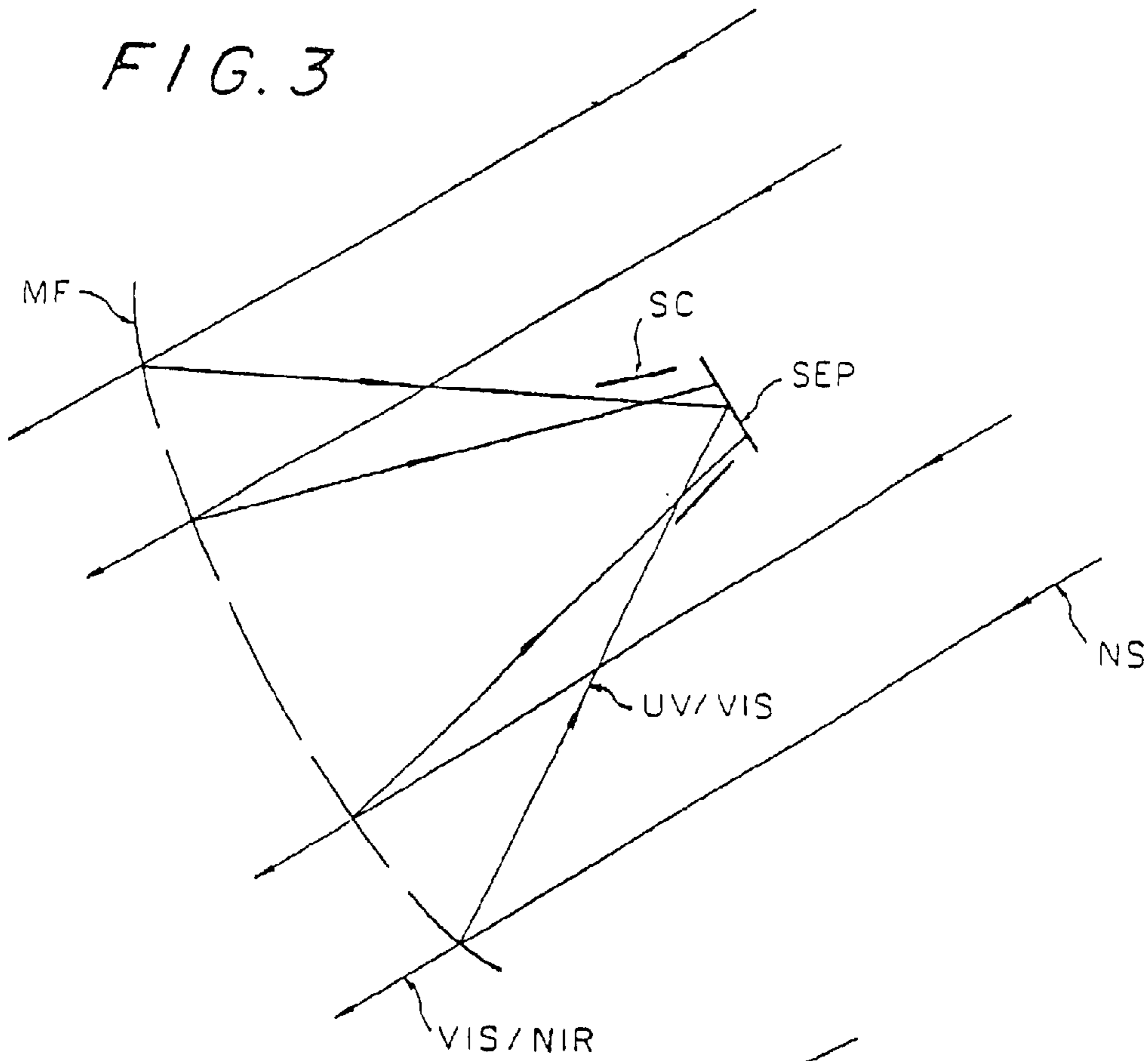


FIG. 4

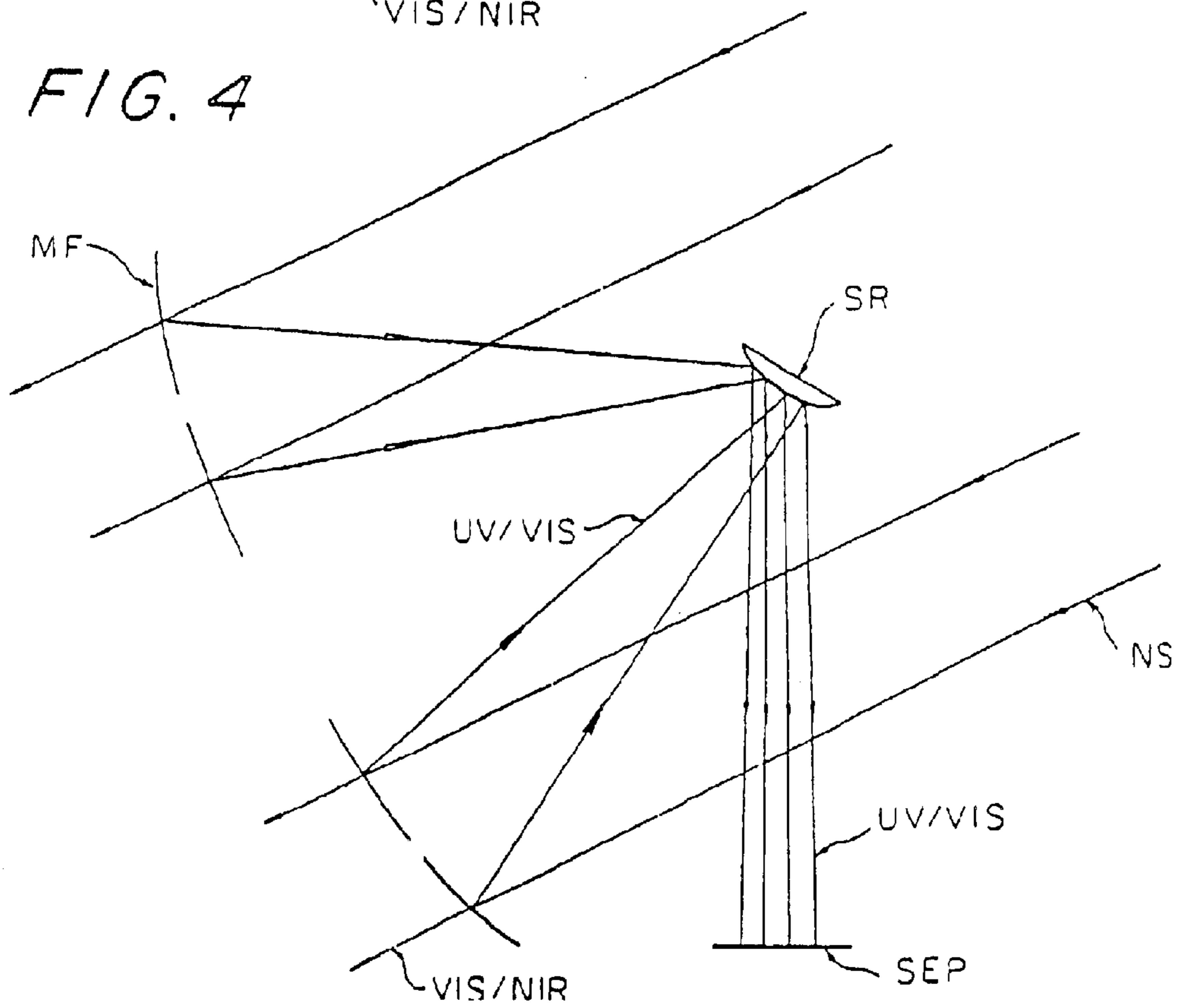


FIG. 5

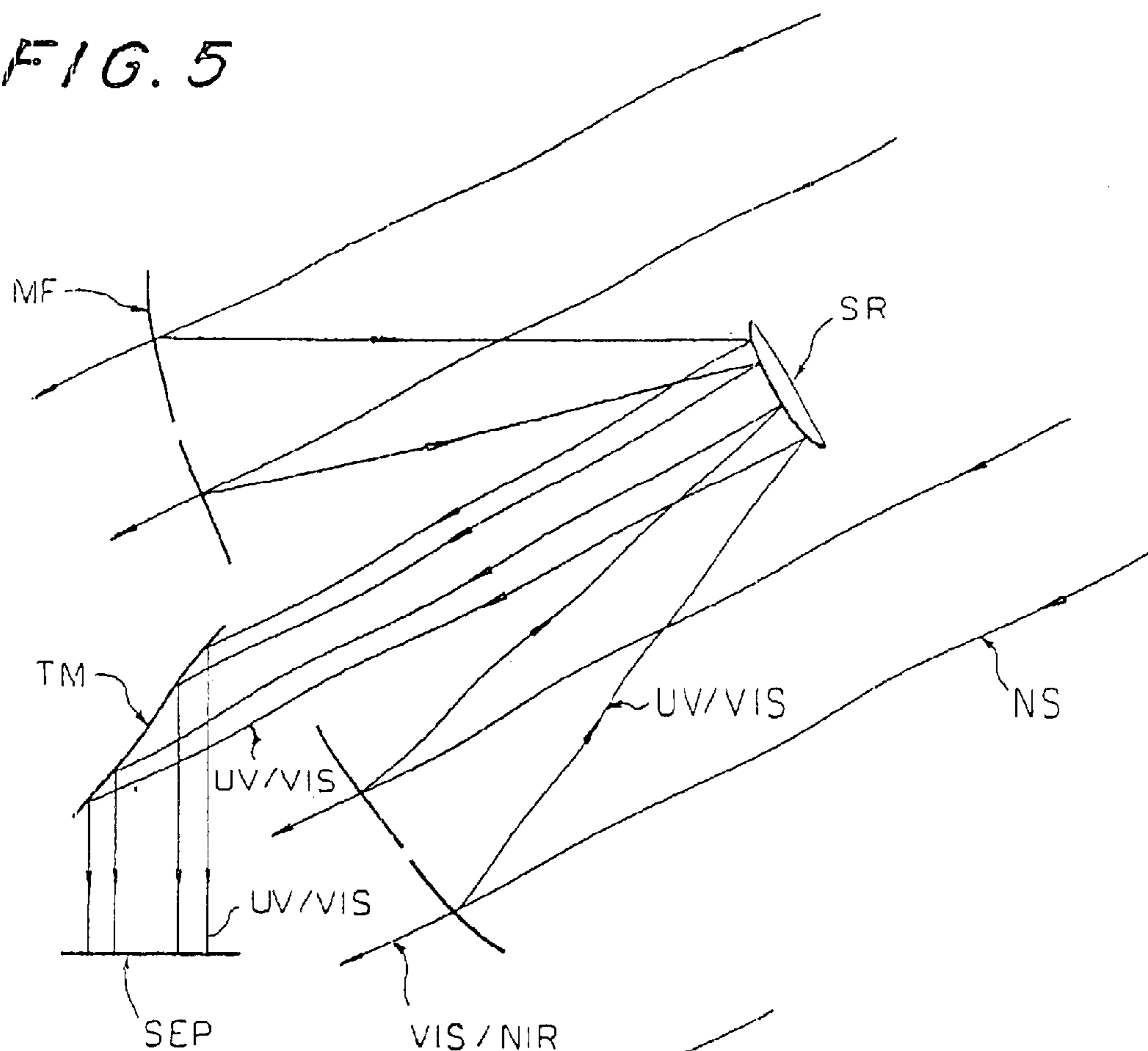


FIG. 6

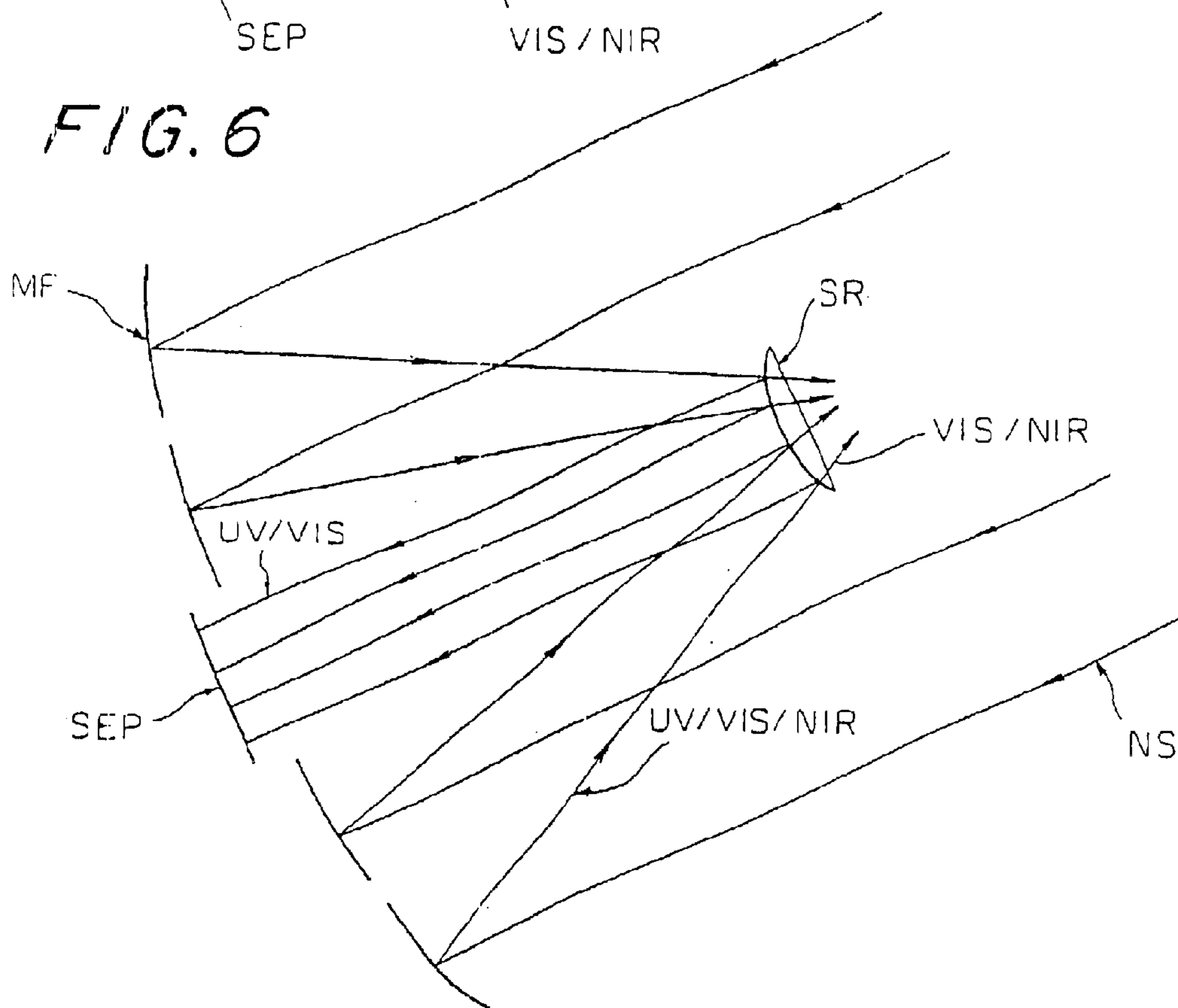


FIG. 7

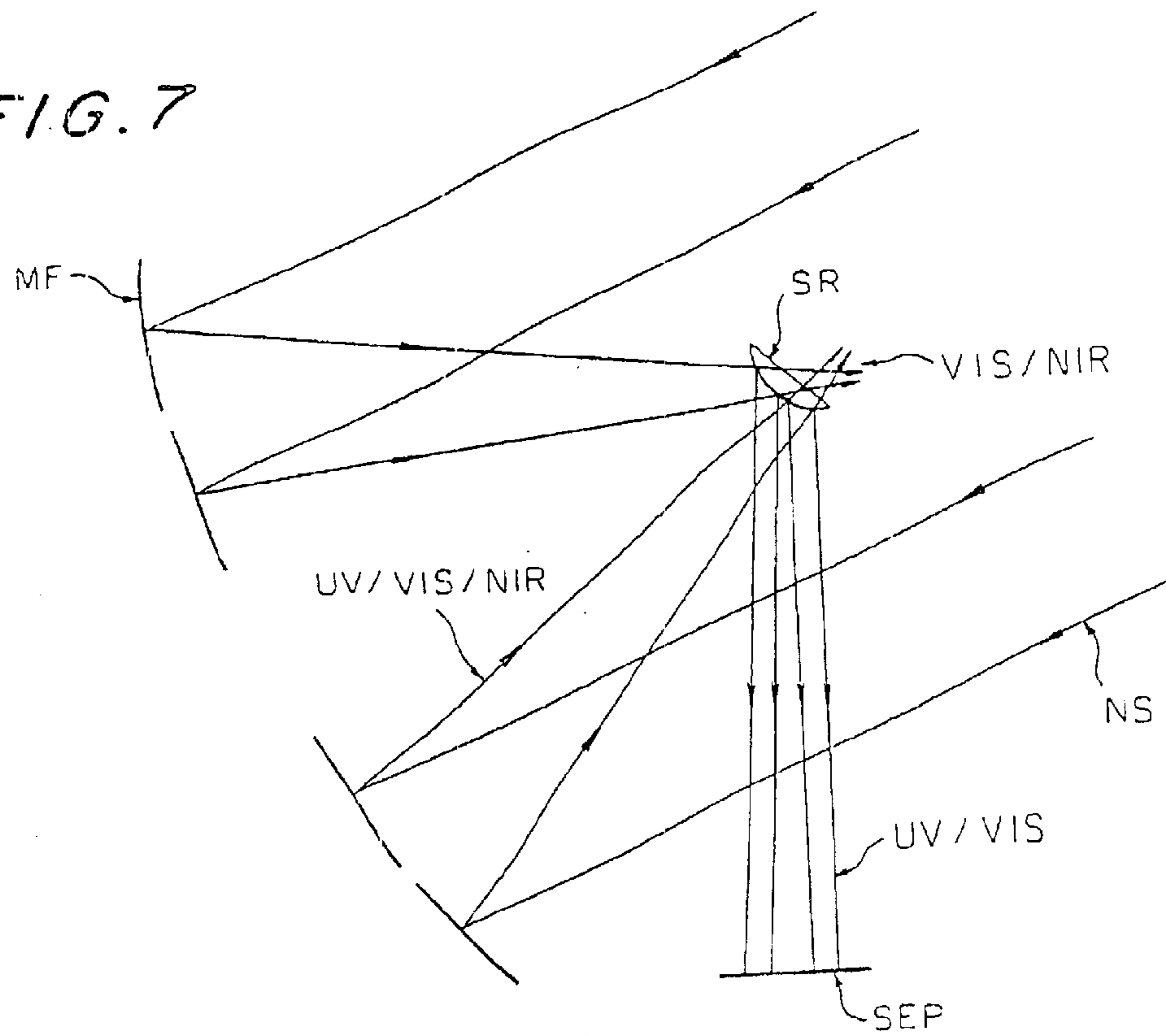


FIG. 8

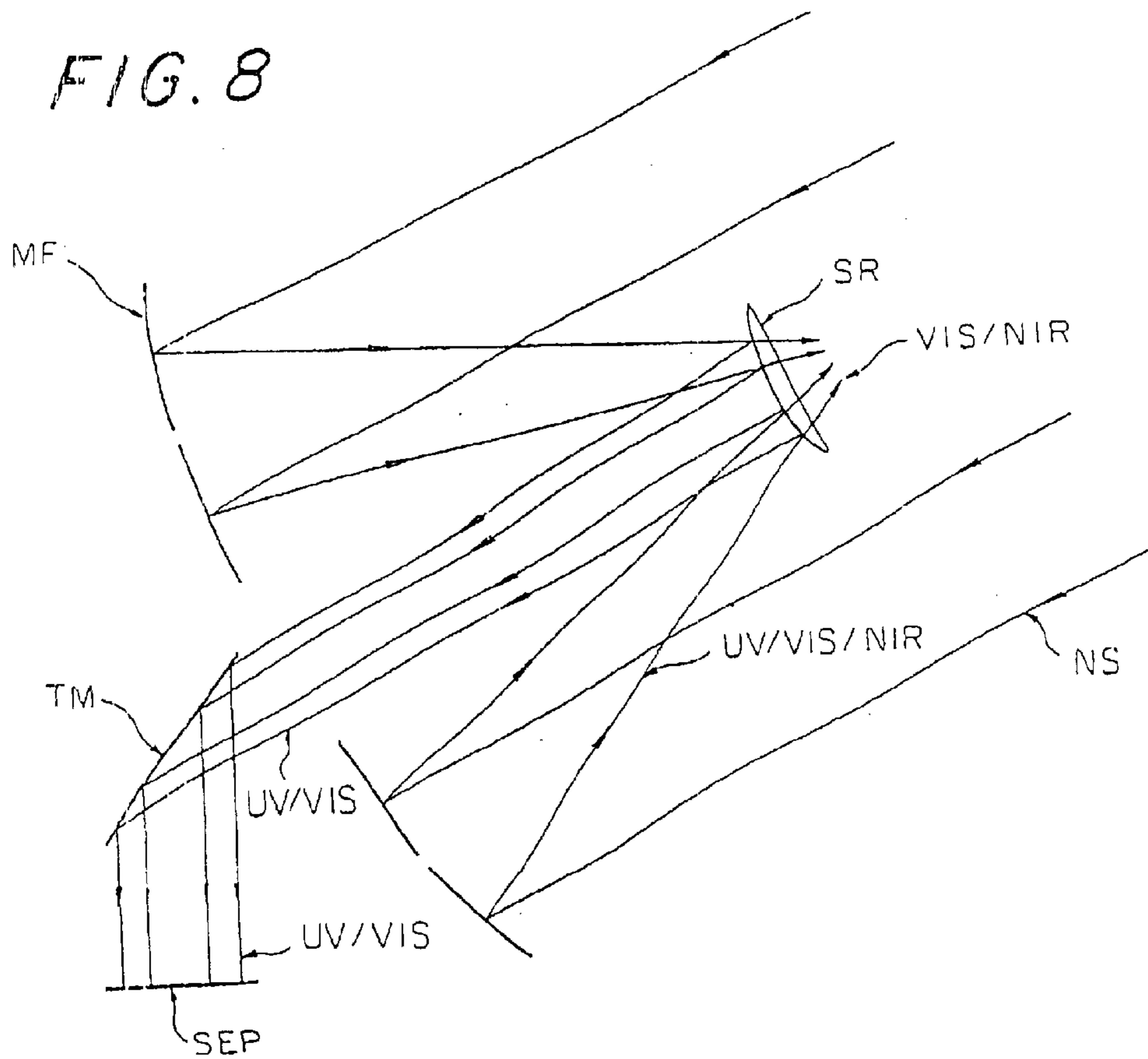


FIG. 9

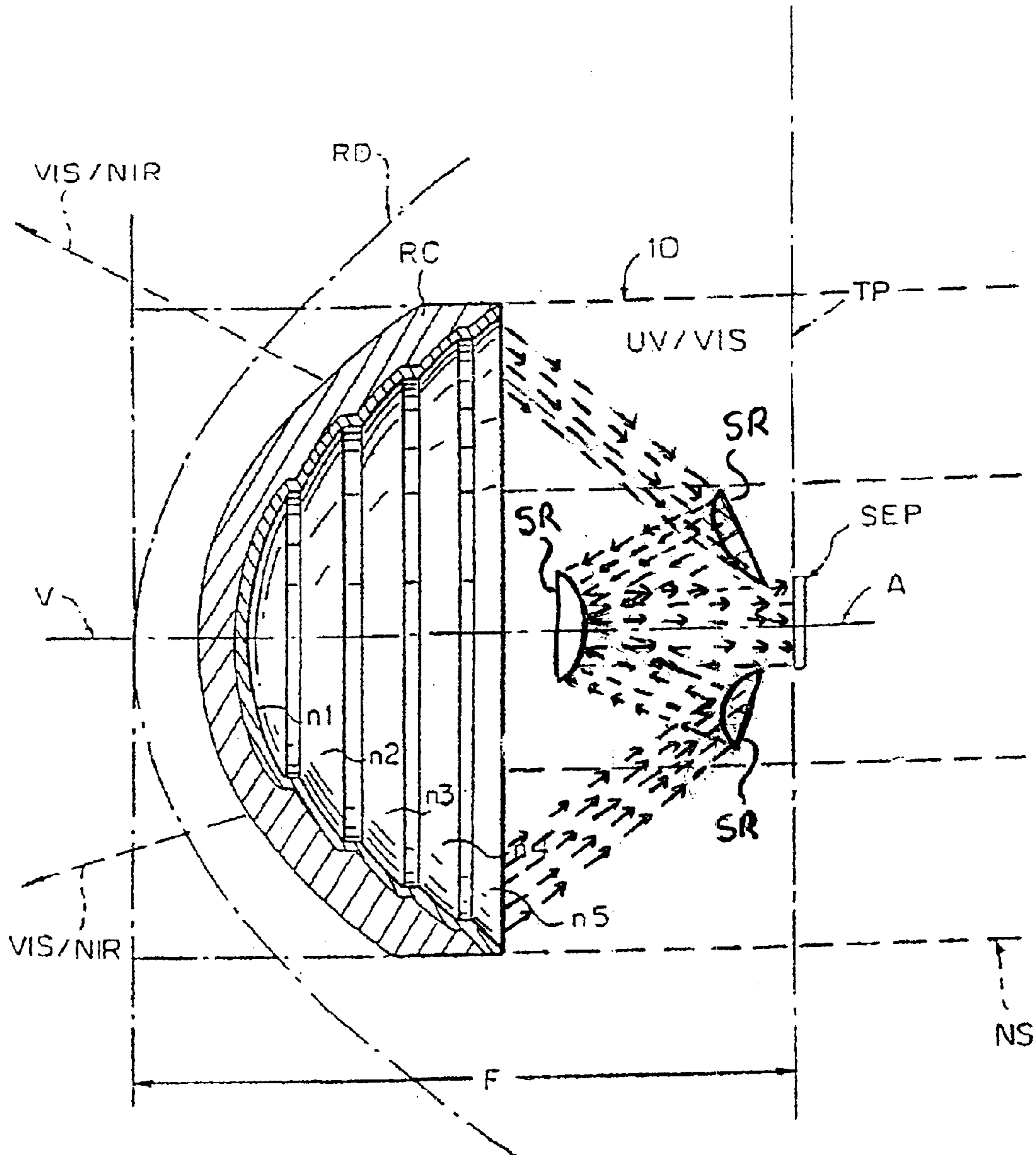


FIG. 9A

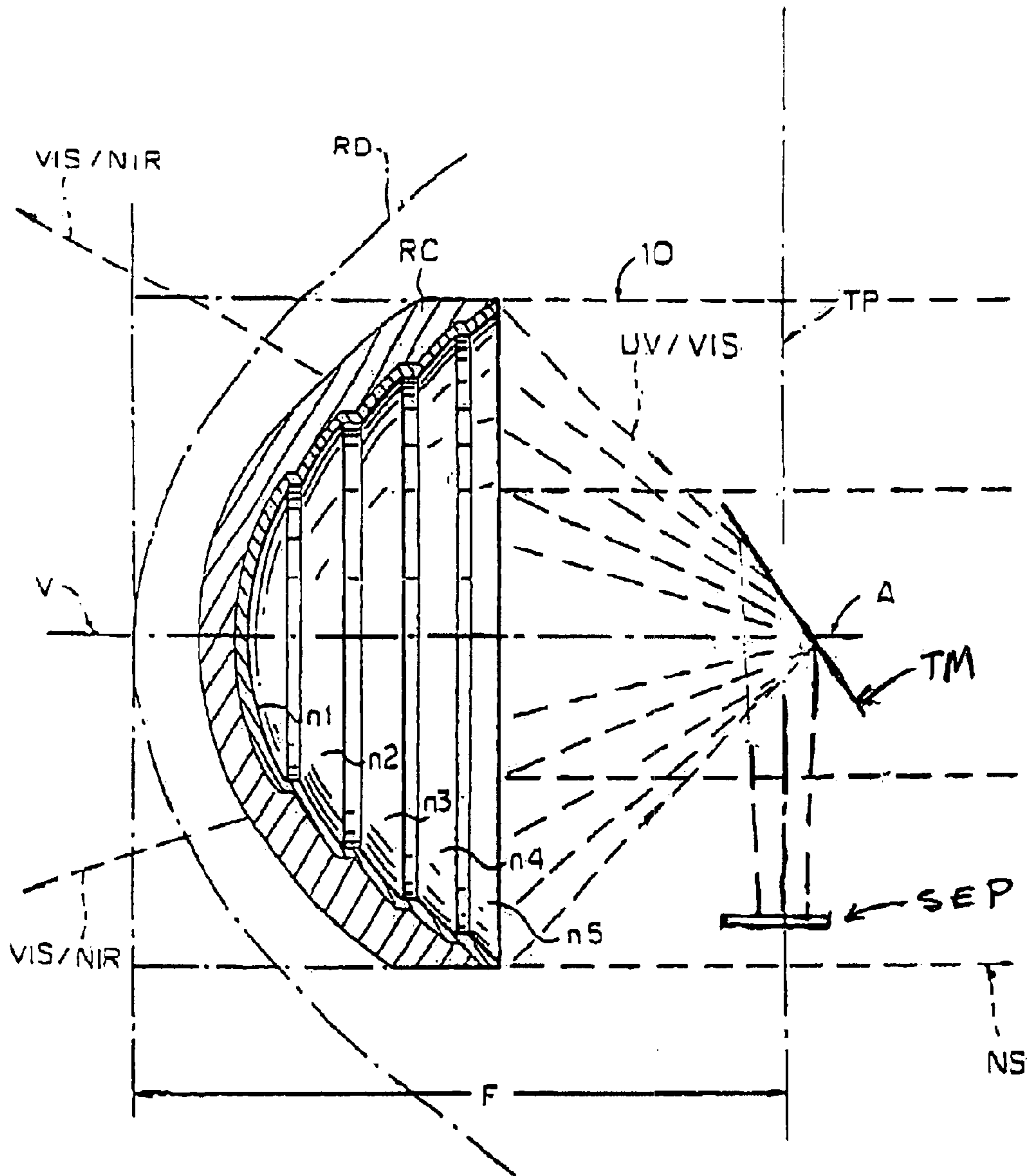


FIG. 10

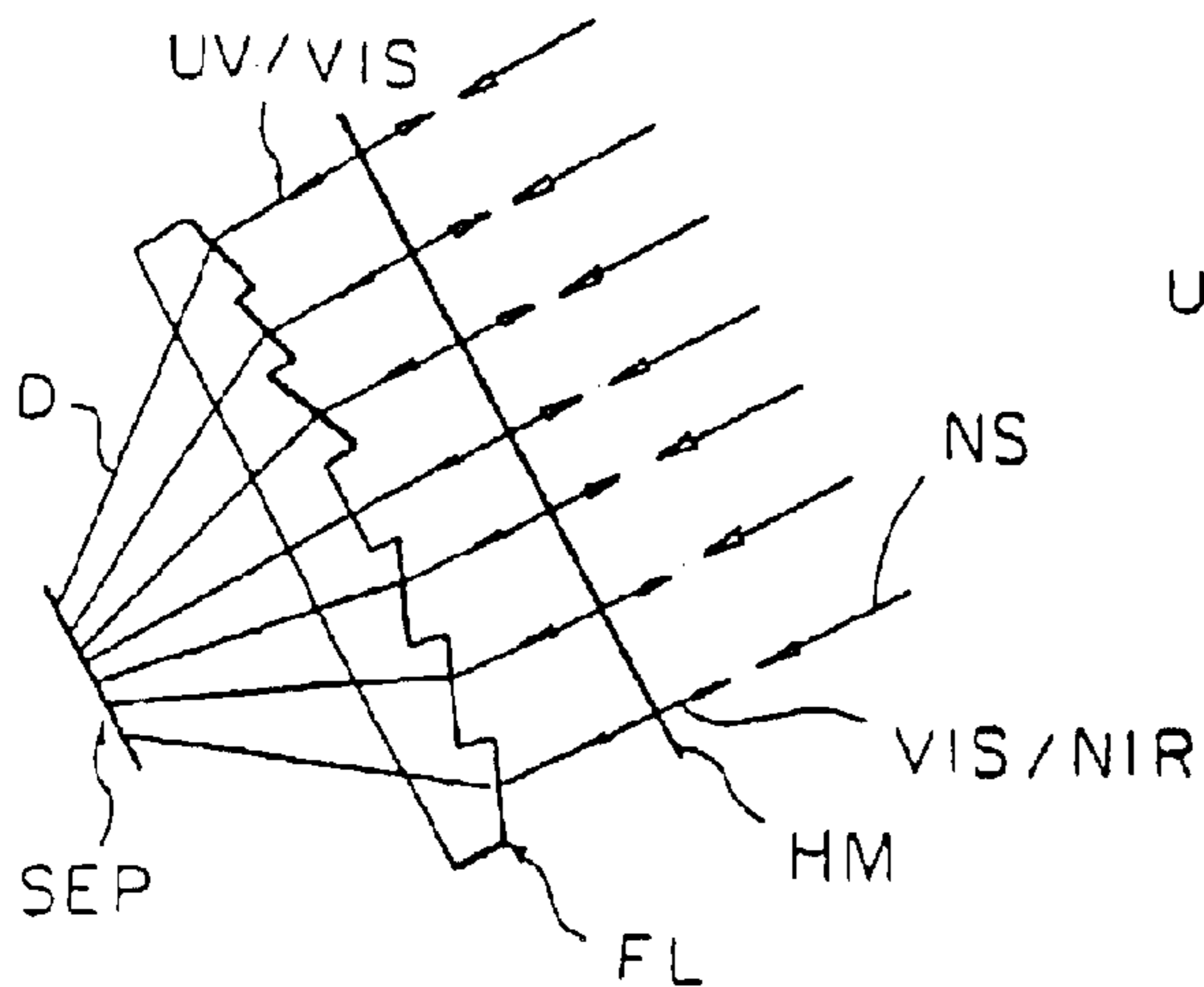


FIG. 11

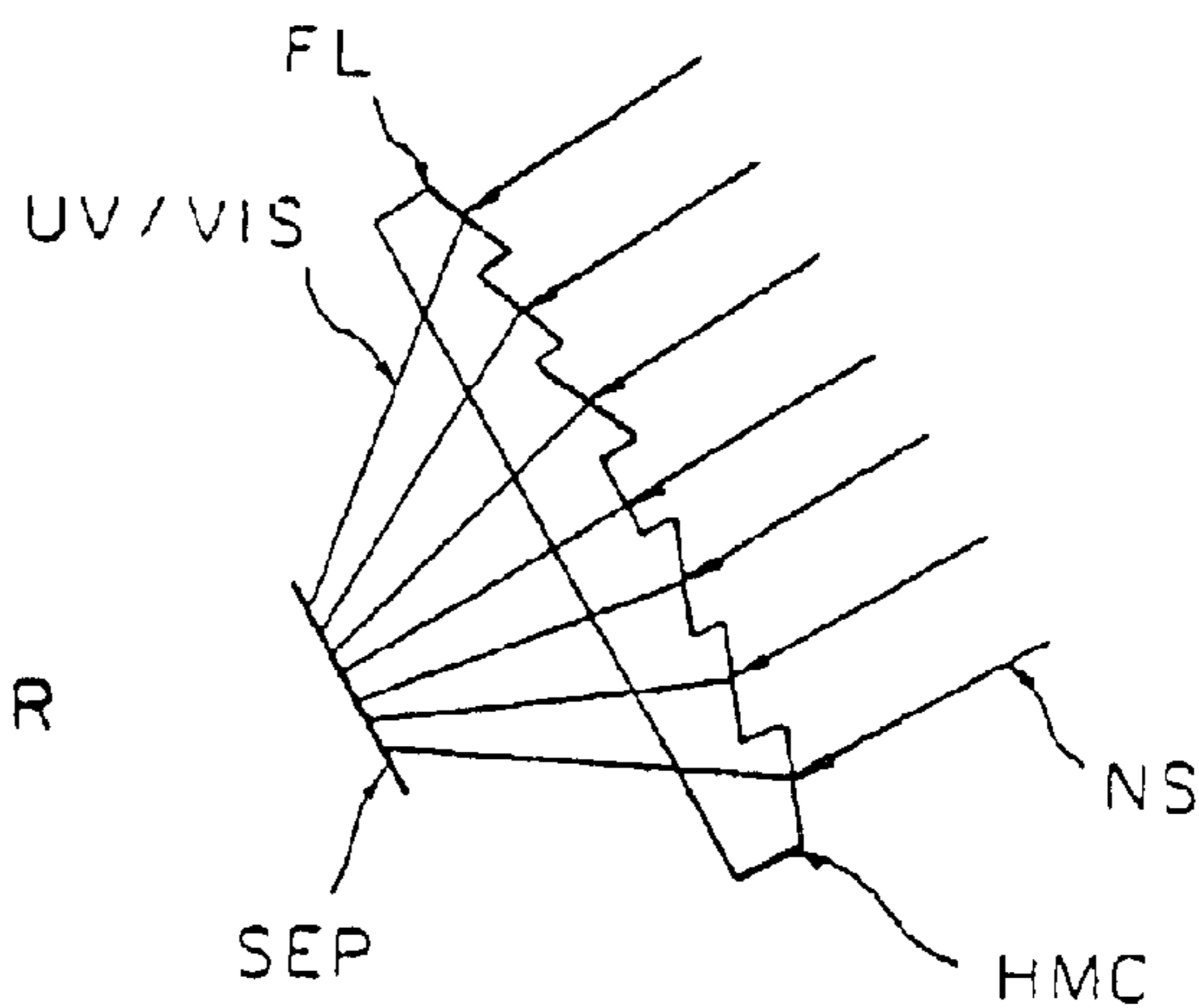


FIG. 12

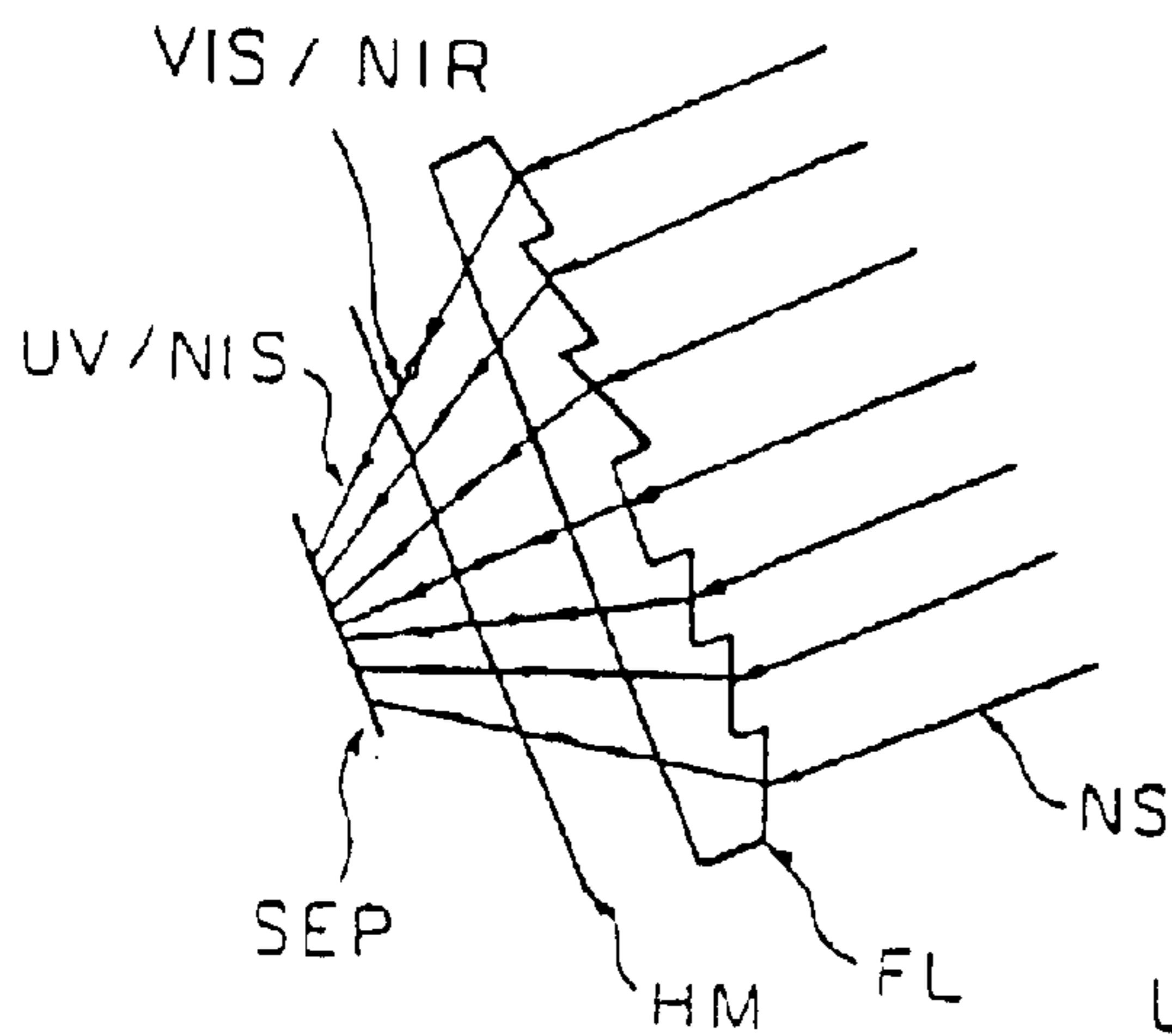


FIG. 13

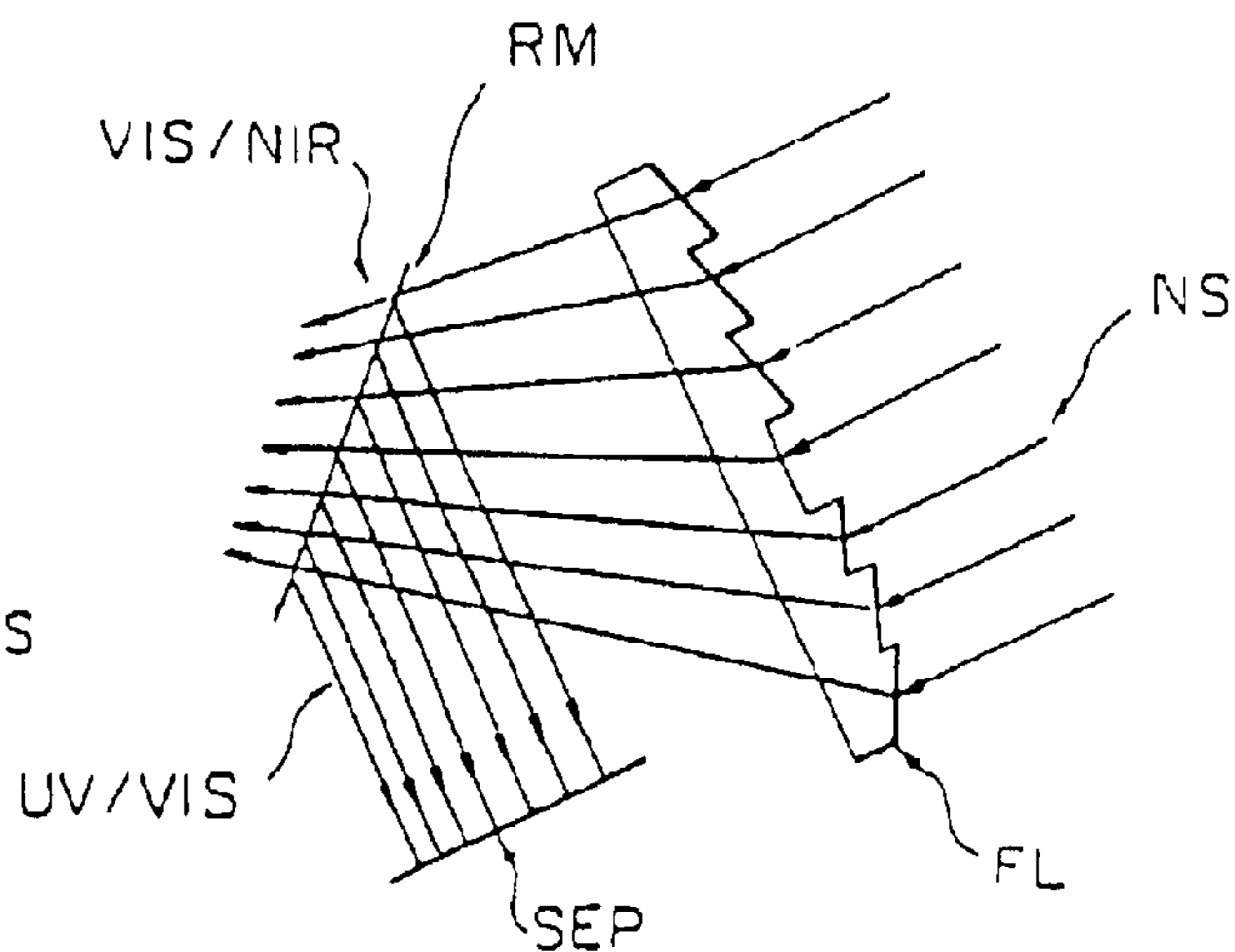




FIG. 14

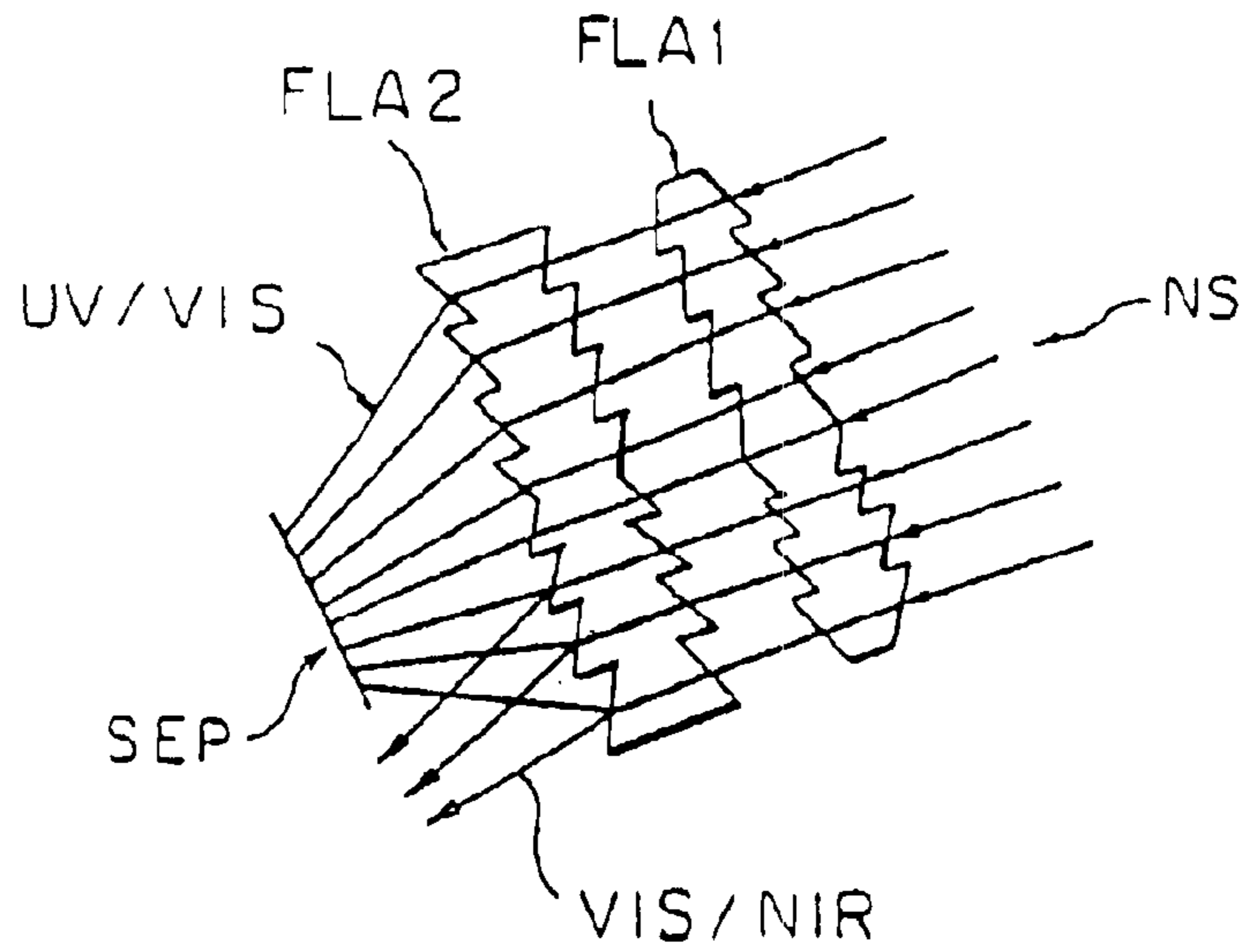


FIG. 15

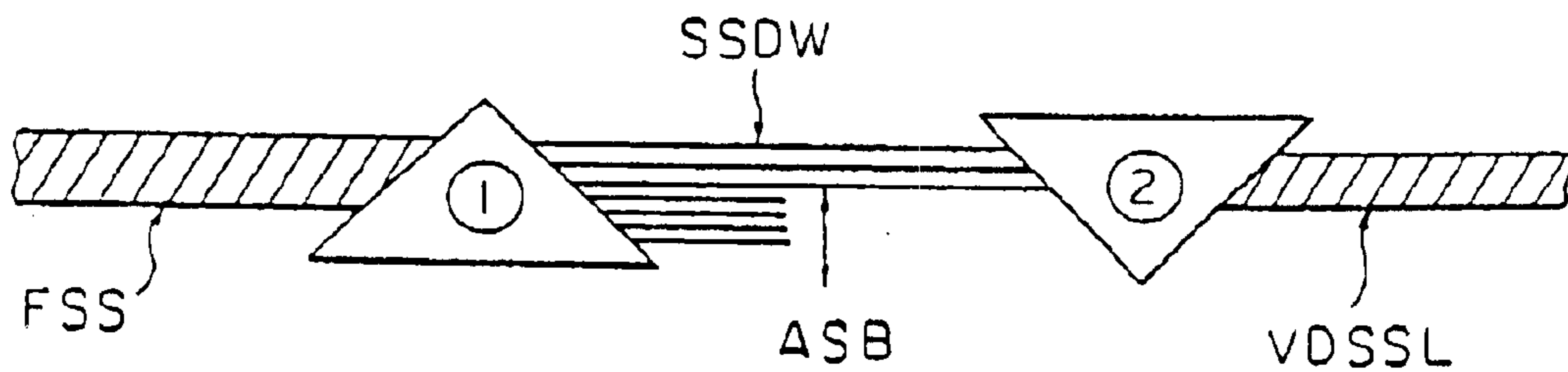


FIG. 16

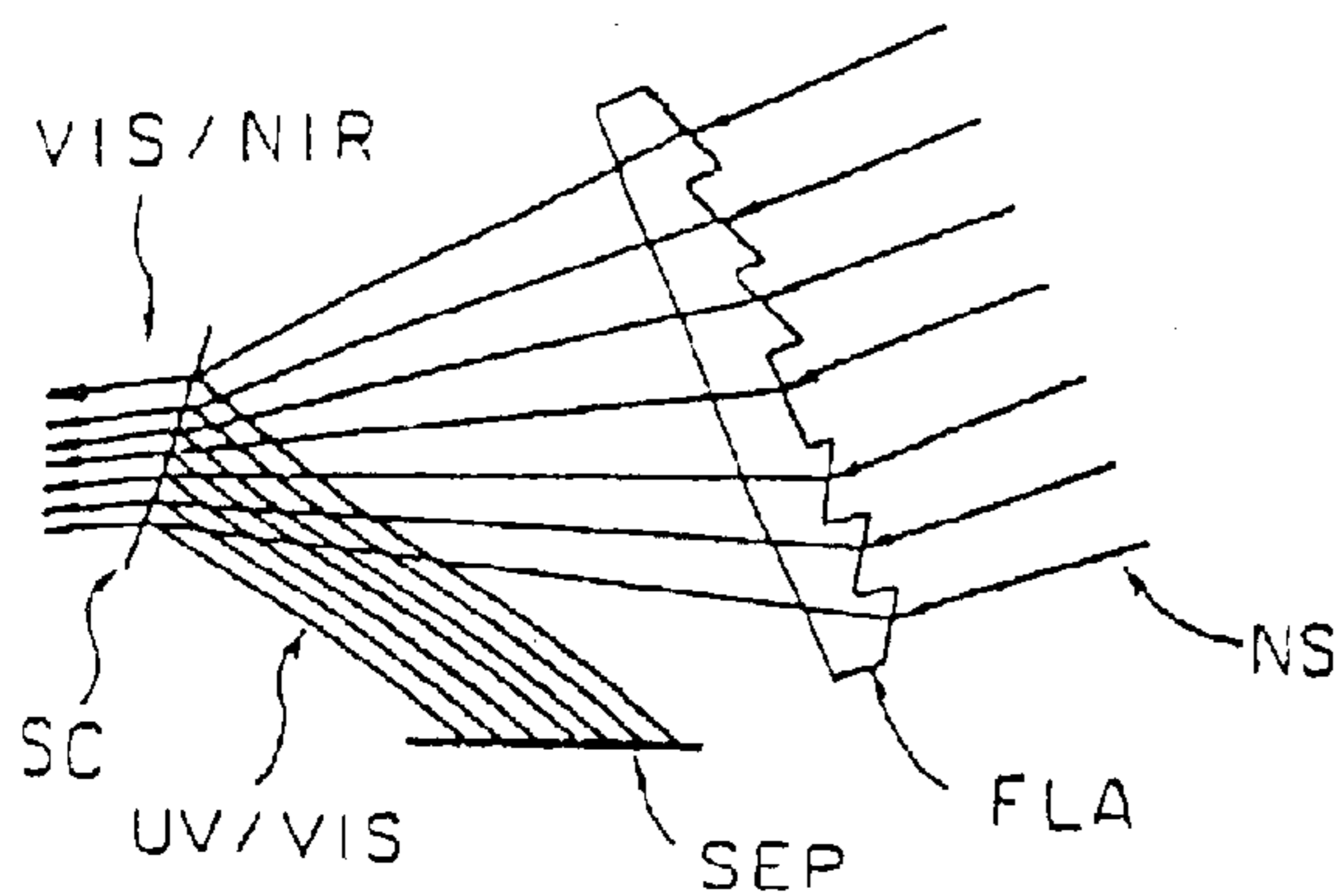


FIG. 17

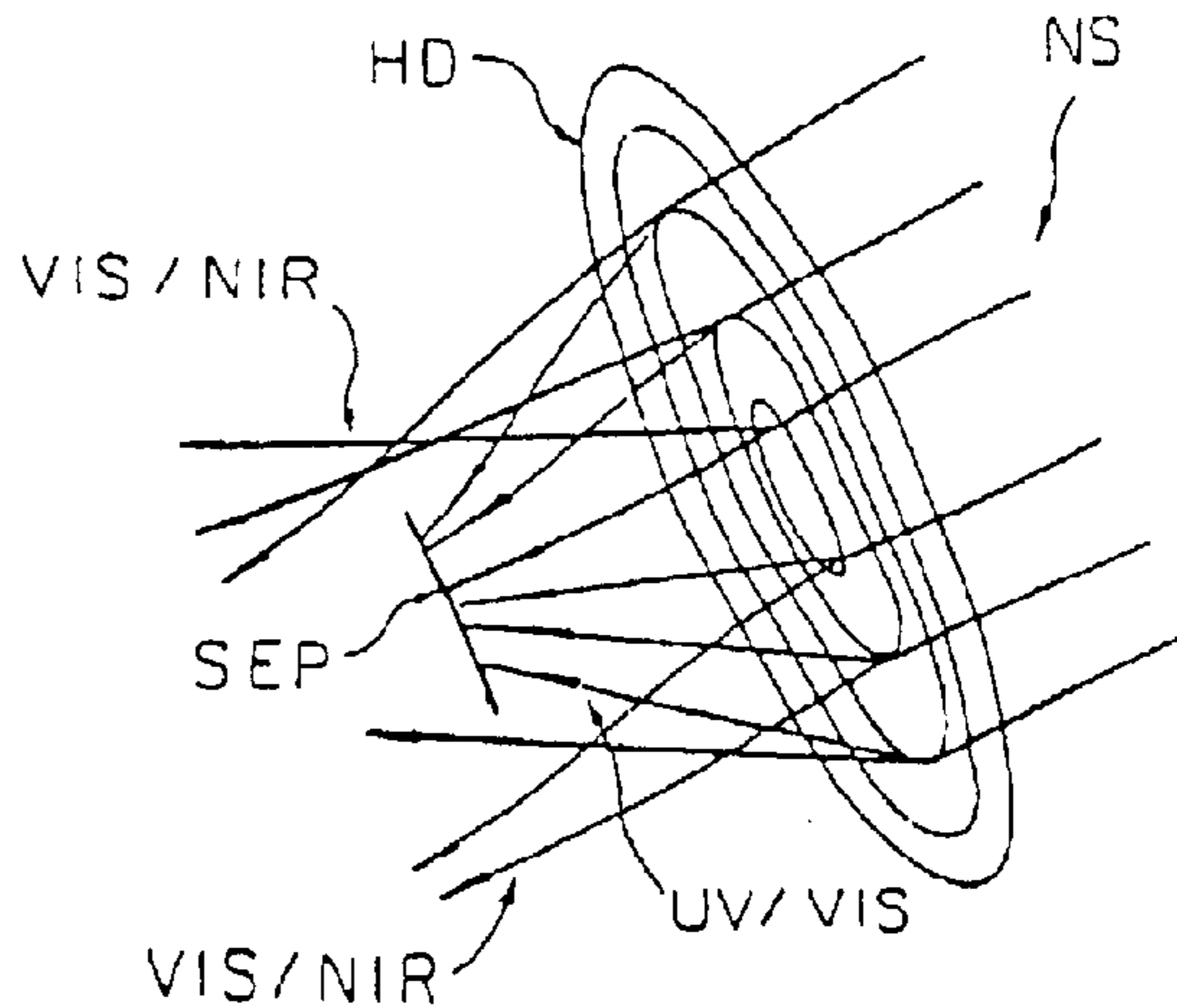


FIG. 18

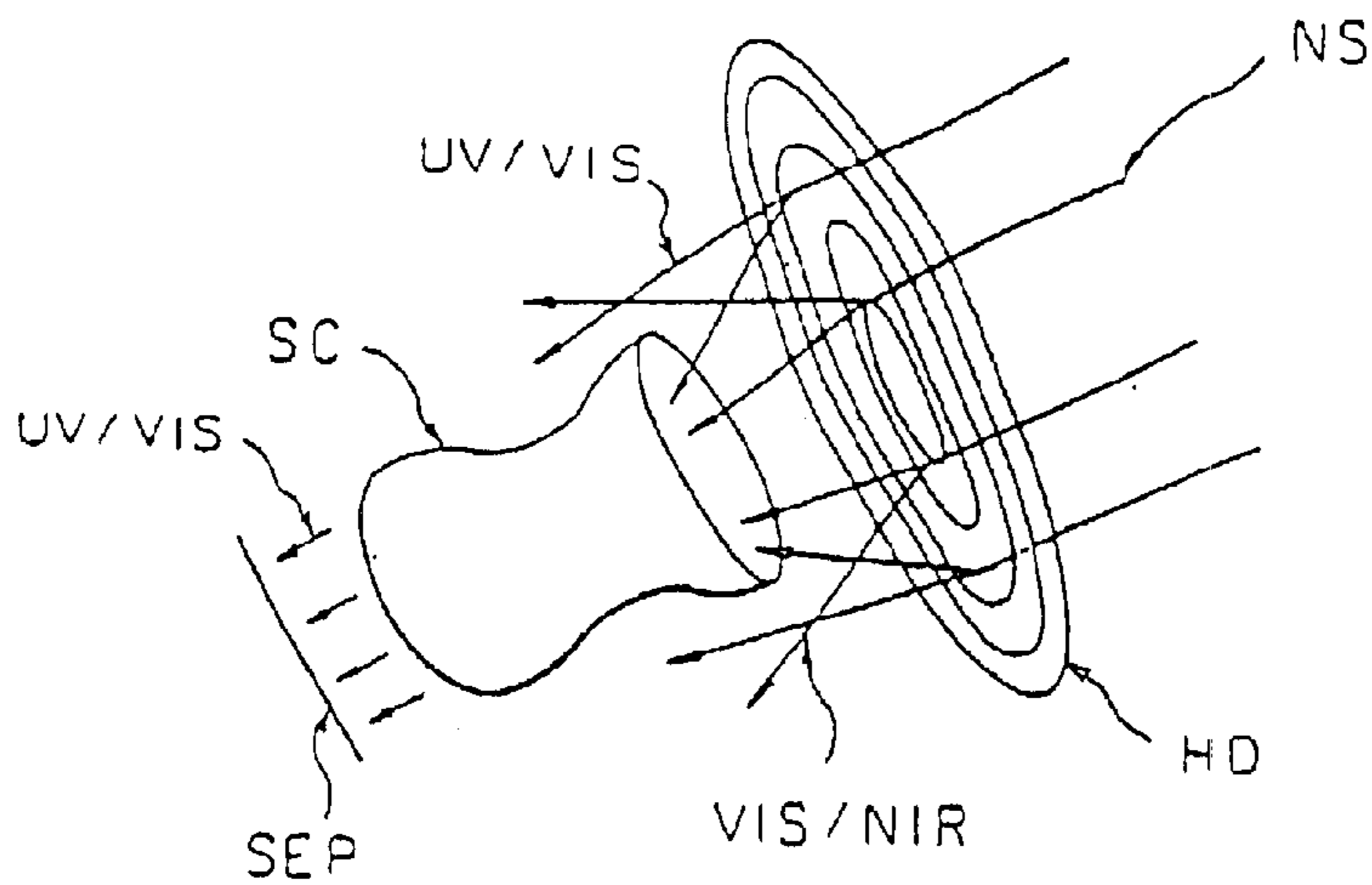


FIG. 19

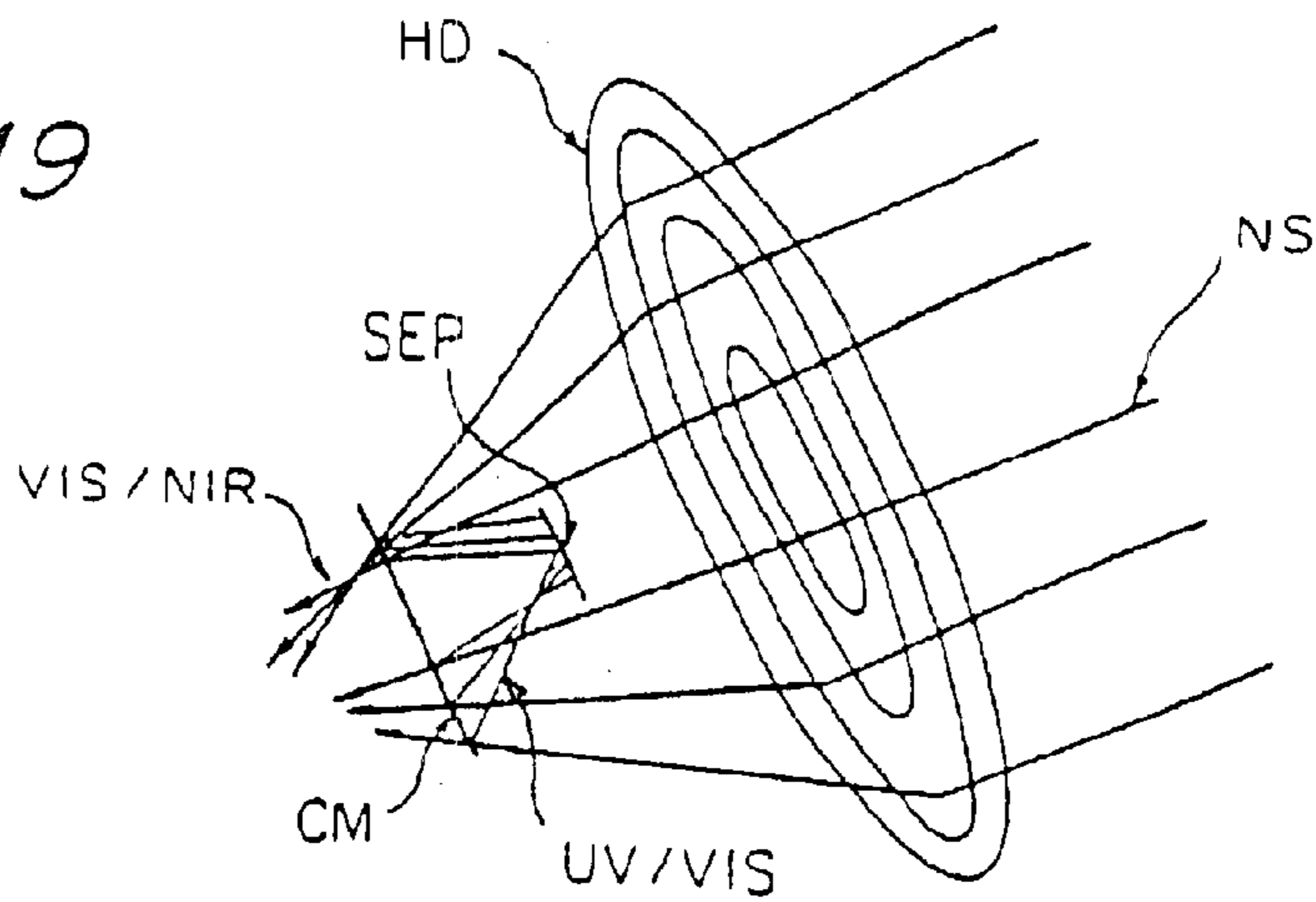


FIG. 20

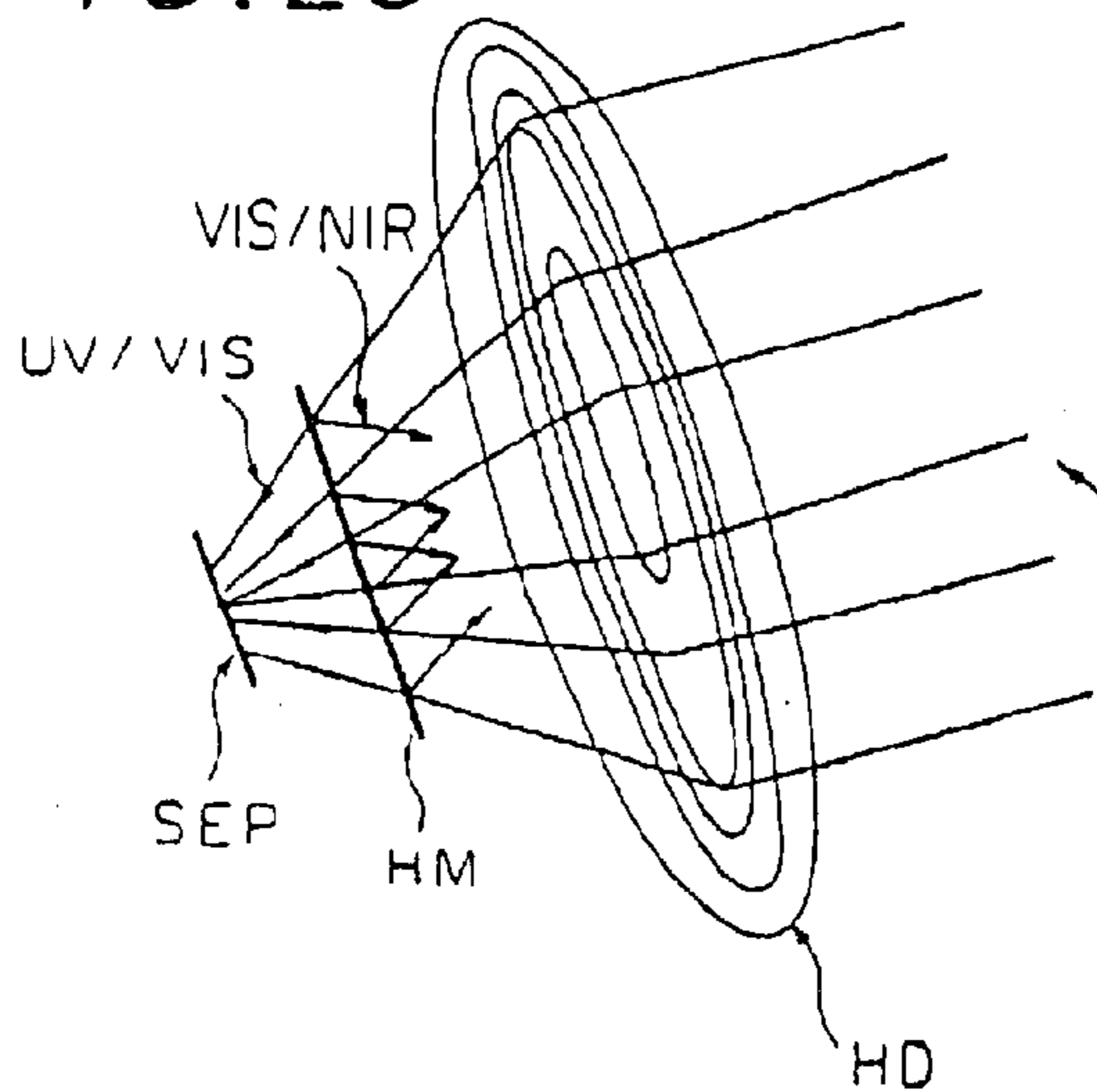


FIG. 21

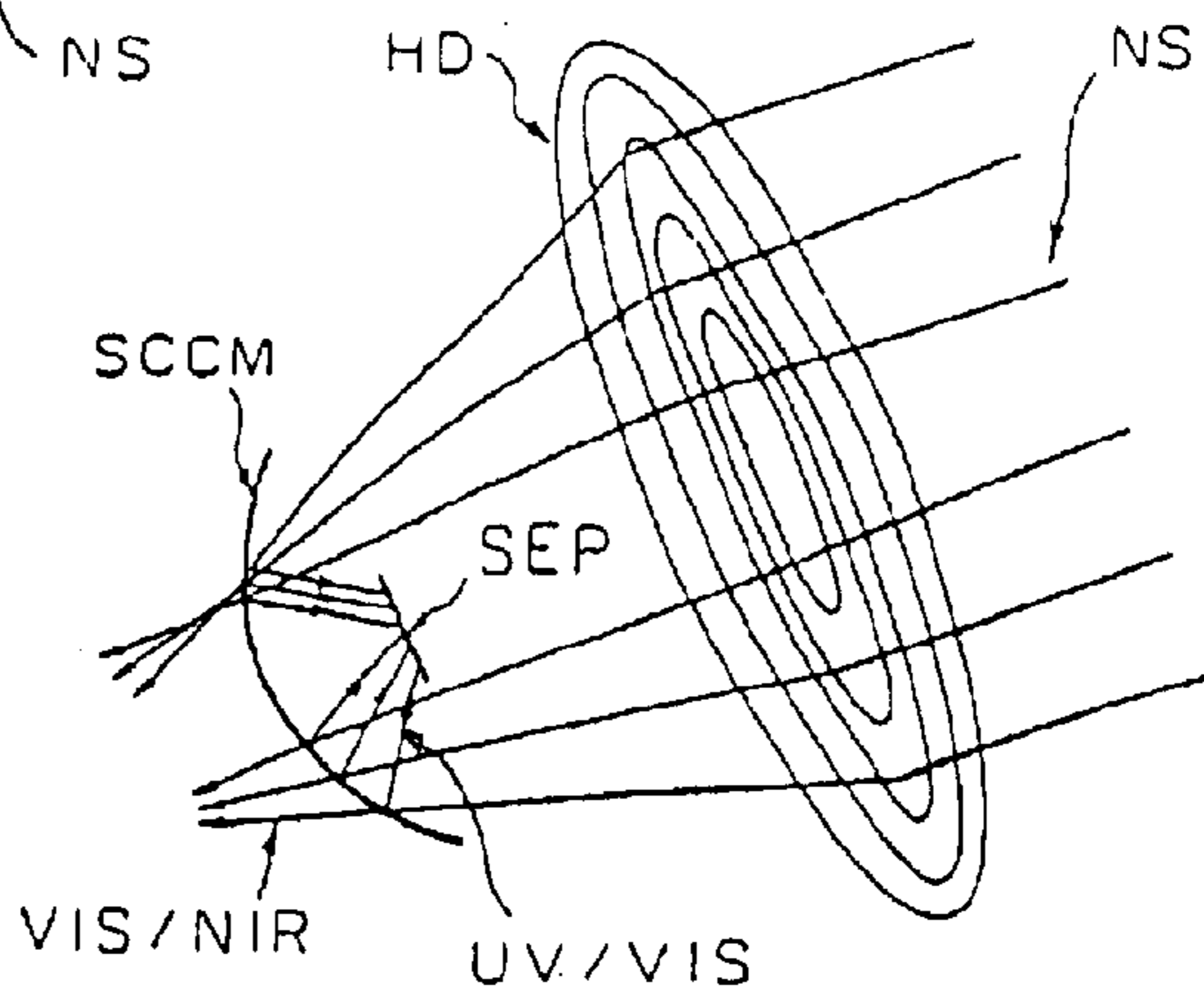


FIG. 22

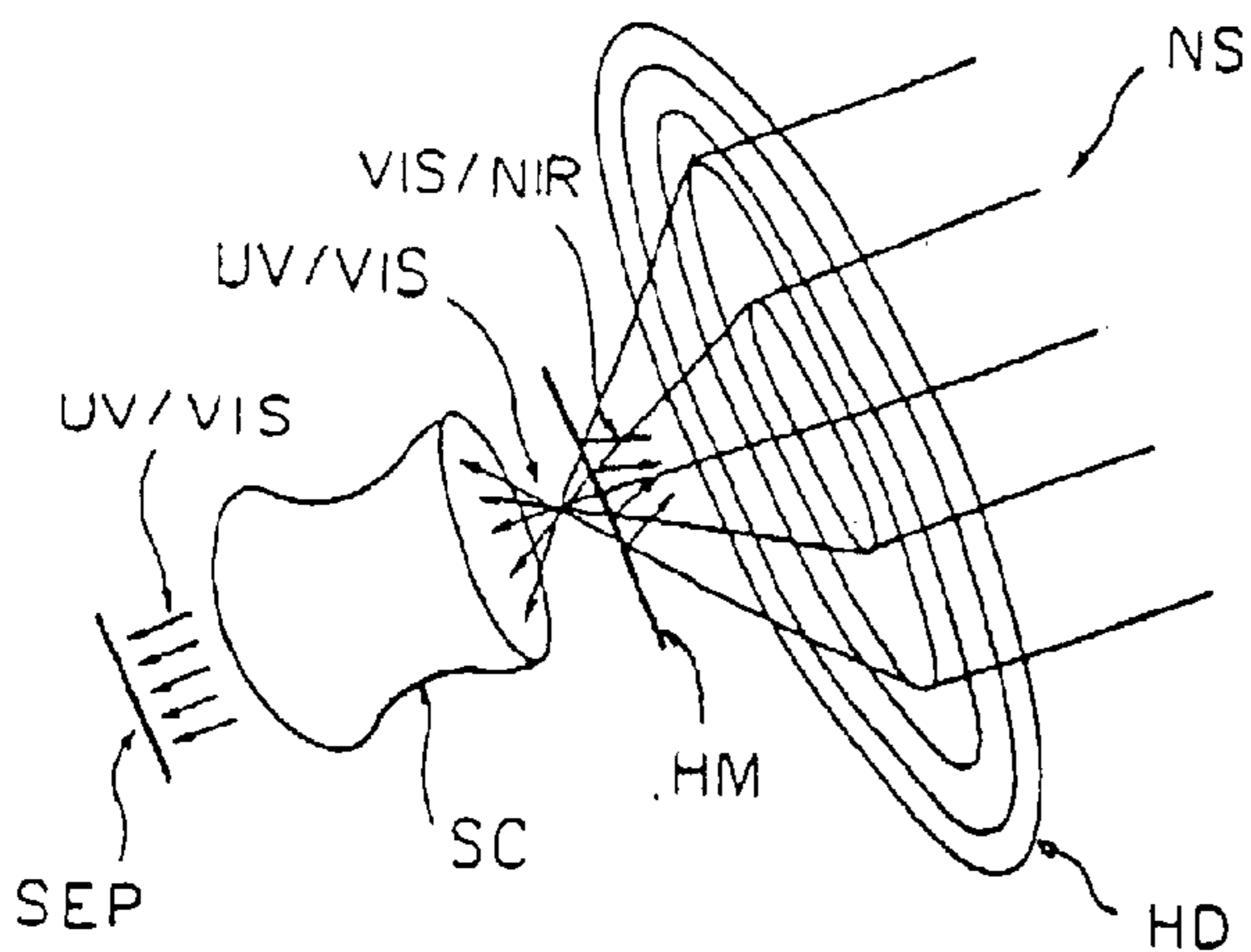


FIG. 23

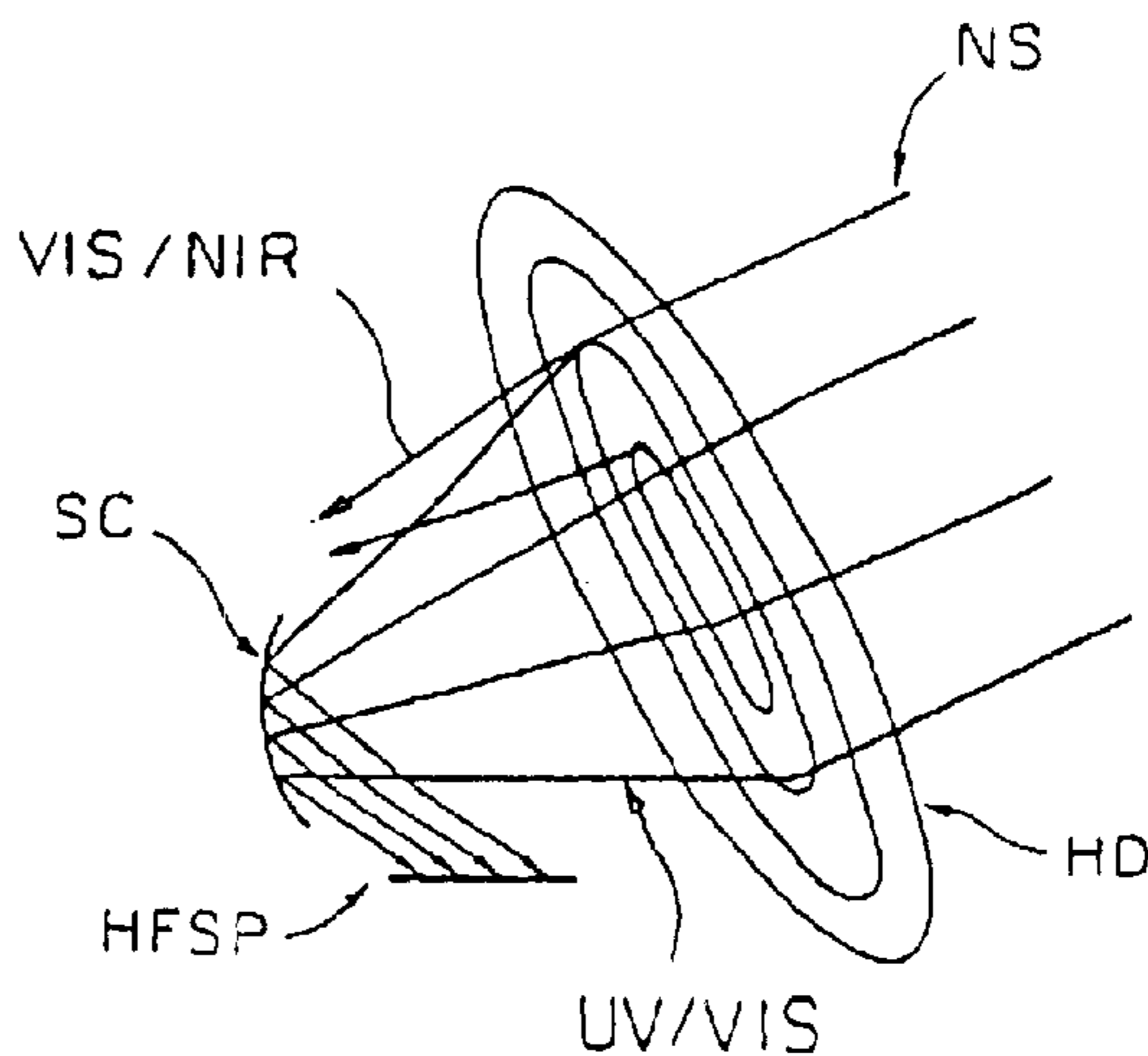


FIG. 24a

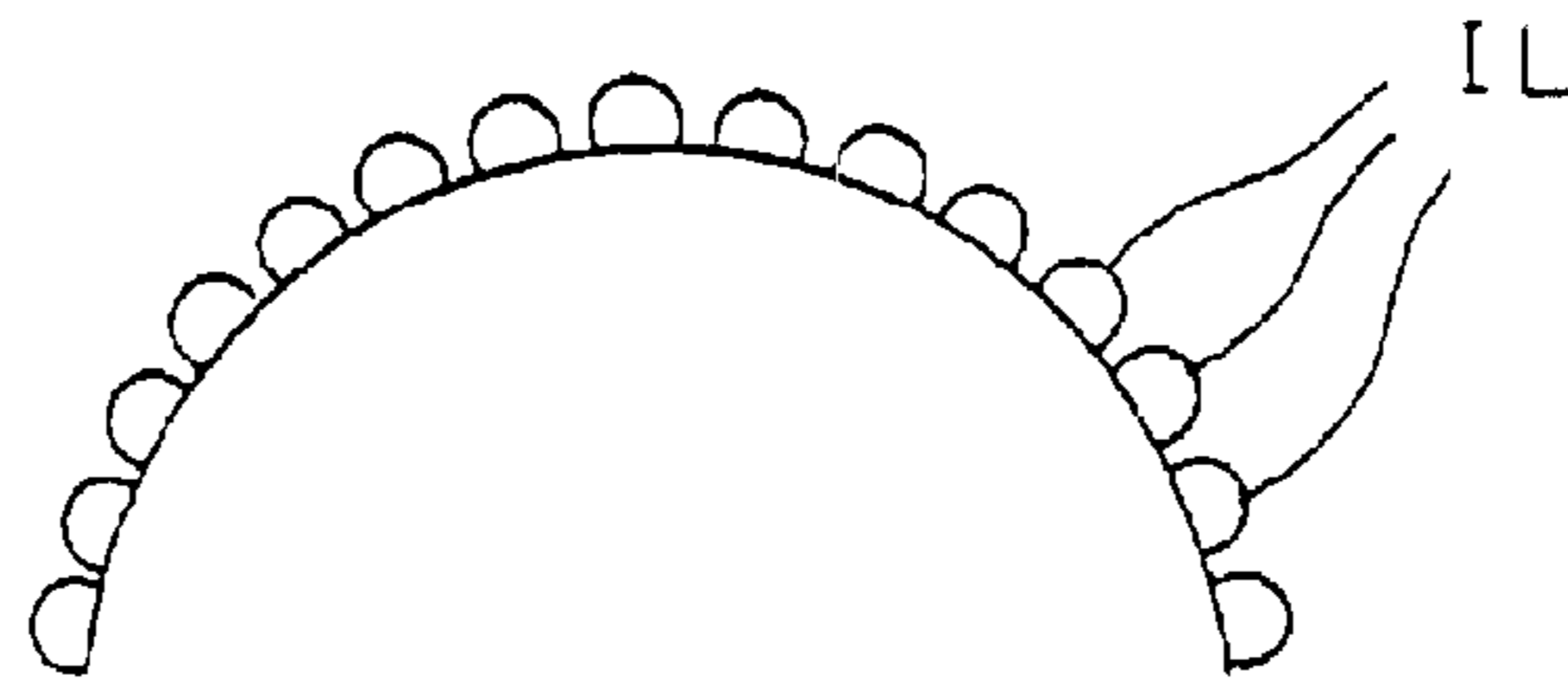


FIG. 24b

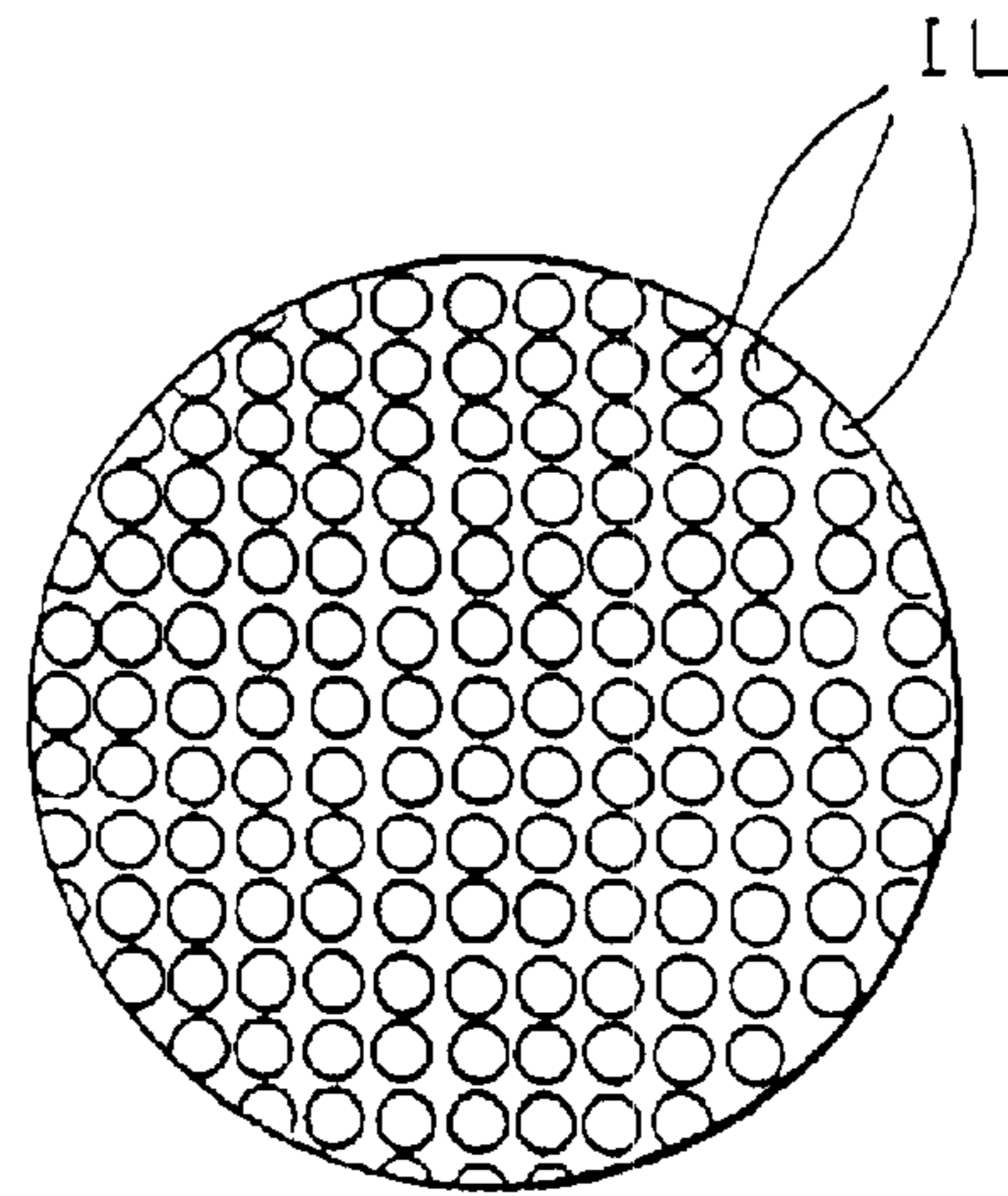


FIG. 25

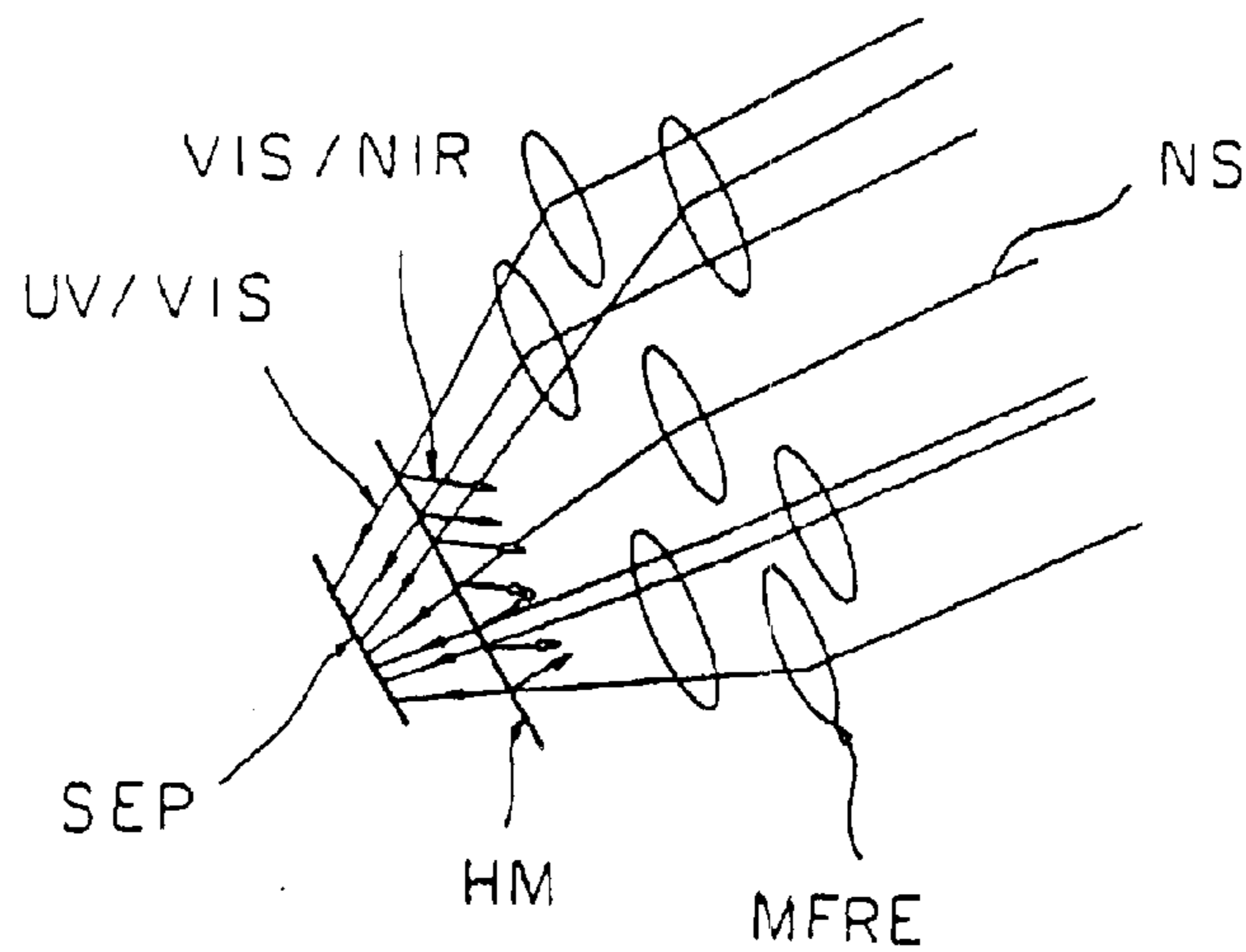


FIG. 26

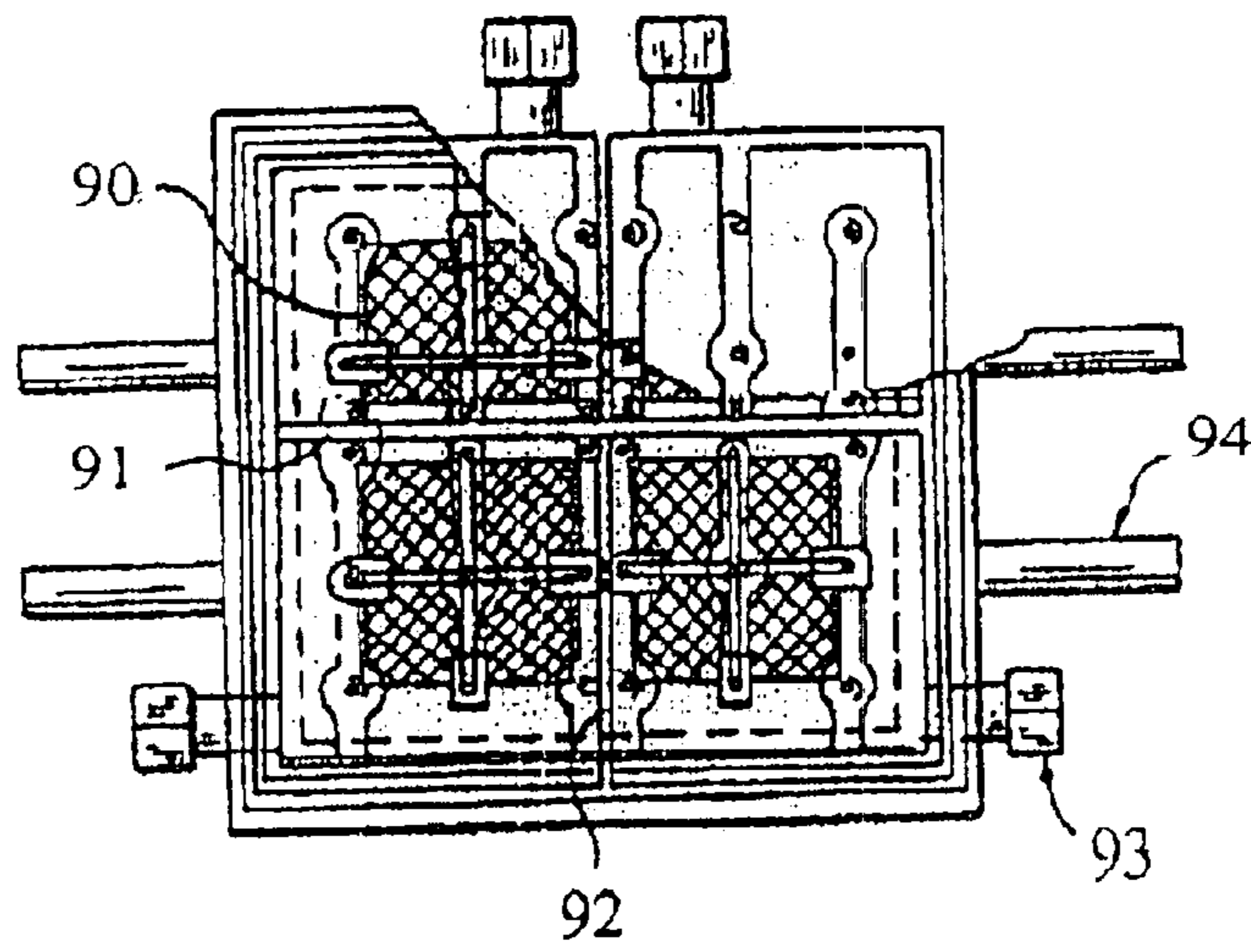


FIG. 27 a

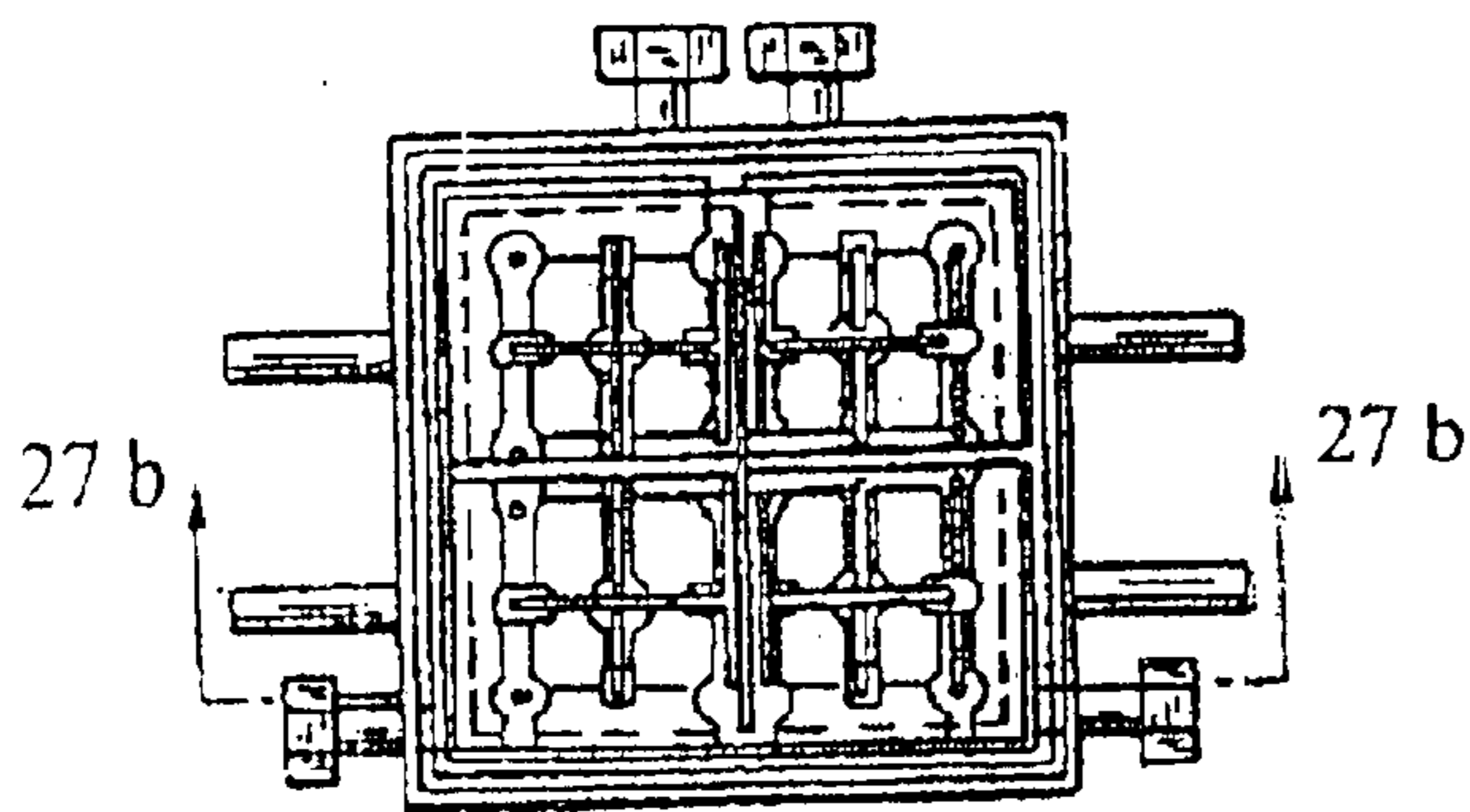


FIG. 27 c

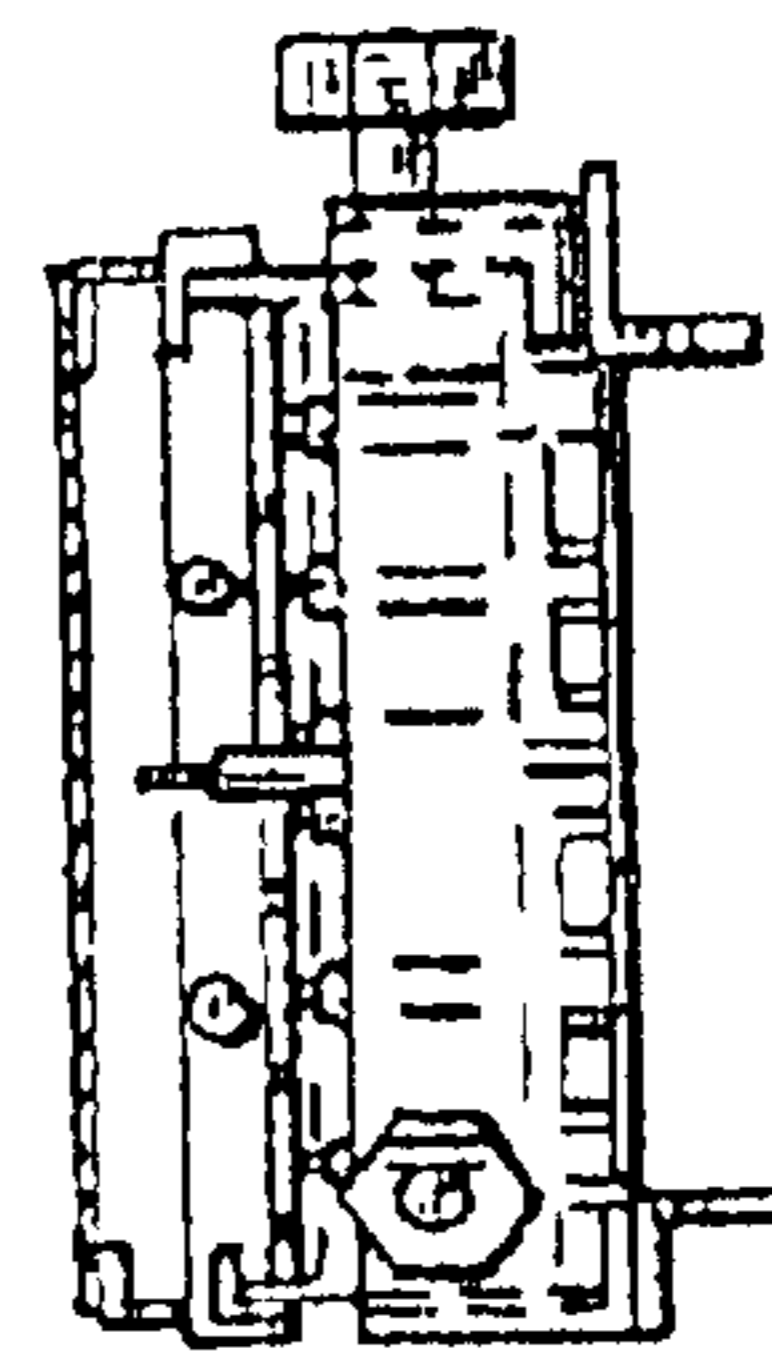
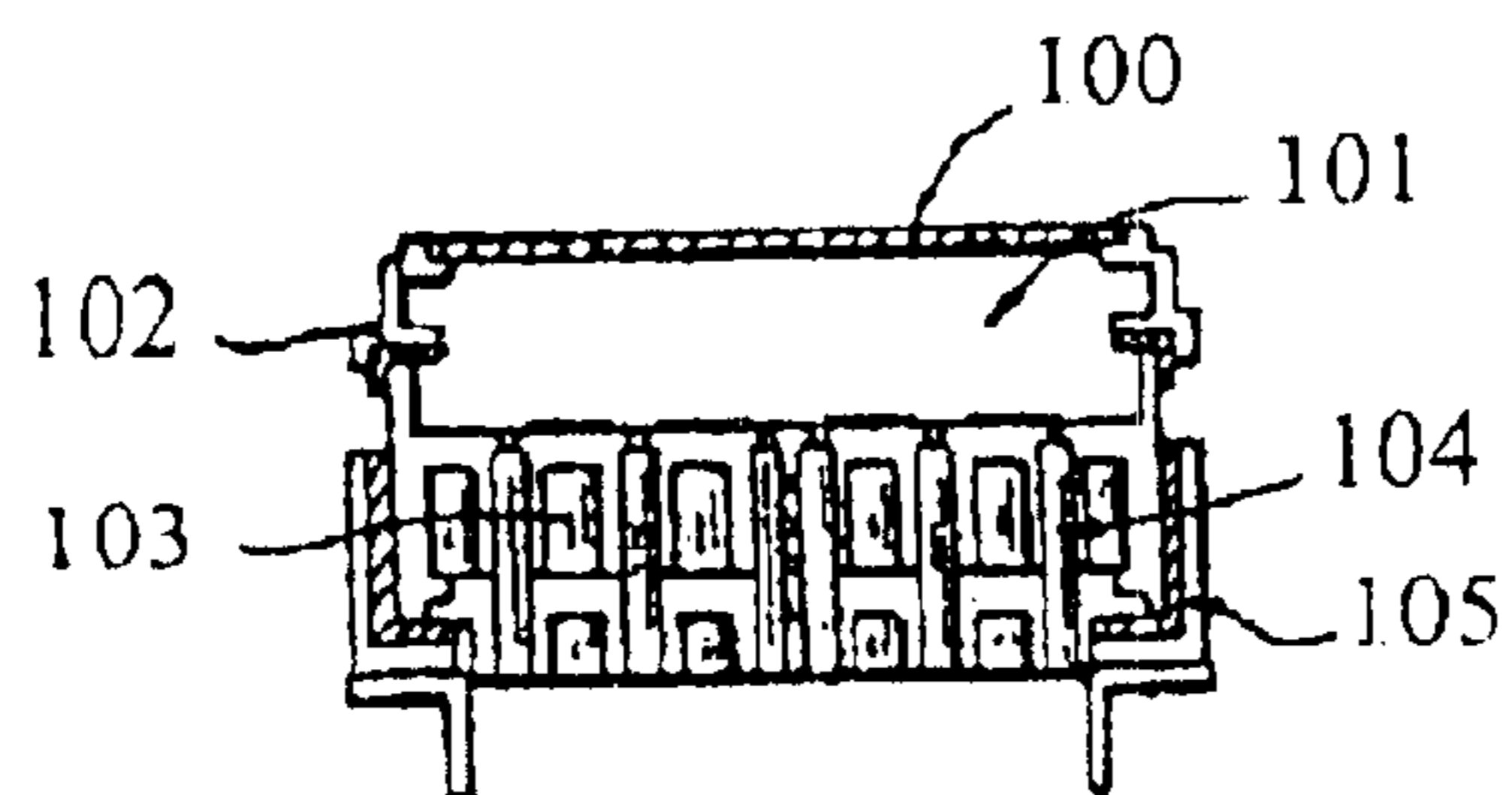


FIG. 27 b





## ULTRA-ACCELERATED NATURAL SUNLIGHT EXPOSURE TESTING FACILITIES

### CROSS REFERENCE TO RELATED APPLICATIONS

This application is a division of U.S. application Ser. No. 09/521,731, filed Mar. 9, 2002, and now U.S. Pat. No. 6,604,436, and which was a continuation-in-part of U.S. application Ser. No. 09/006,746, filed Jan. 13, 1998, and now U.S. Pat. No. 6,073,500.

### CONTRACTUAL ORIGIN OF THE INVENTION

The United States Government has rights in this invention pursuant to Contract No. DE-AC36-83CH10093 between the United States Department of Energy and the Midwest Research Institute.

### BACKGROUND

#### 1. Field of the Invention

The invention relates to apparatus for subjecting materials to accelerated irradiance exposure factors that permit about a year's worth of representative weathering to be accumulated in a period from about 3 to about 10 days, under controlled weathering conditions that include several concurrent levels of temperature and/or relative humidity at very high levels of natural sunlight.

In the invention process, a solar concentrator [which may include a High Flux Solar Furnace (HFSF) and an Irradiance Redistribution Guide (IRG)] is used to obtain elevated levels (25–100×) of concentrated sunlight for accelerated testing of material samples. When an IRG is used, it provides the capability of being able to modify (redistribute) the Gaussian-shaped beam from the HFSF into a more uniform profile on a sample exposure plane.

Also encompassed in the invention process for obtaining ultra-accelerated natural sunlight exposure testing is the use of reflective apparatus such as multi-step and multi-faceted concentrators and refractive apparatus such as Fresnel lens concentrators, holographic concentrators, 2D or 3D micro lens arrays, and an array of Fresnel lens facets to obtain elevated levels (25–100×) of concentrated sunlight for accelerated natural sunlight testing of material samples.

By adequately controlling sample temperatures and demonstrating that reciprocity relationships are obeyed (i.e., the level of applied accelerated stresses does not change the failure/degradation mechanism), this novel capability allows materials to be subjected to accelerated irradiance exposure factors of 25–100×, thereby permitting a year's worth of representative weathering (in terms of natural sunlight exposure) to be accumulated in from about 3 to about 10 days.

#### 2. Description of the Prior Art

U.S. Pat. No. 4,817,447 discloses a weathering chamber using lamps and sample temperature control using cooling air. Uniform sample irradiance at accelerated levels of up to 10 suns (within the UV bandwidth) appears attainable.

A test apparatus incorporating a mirror, which rejects infrared, is disclosed in U.S. Pat. No. 4,012,954. In the '954 patent, convective cooling air and a conductively cooled substrate are also incorporated. However, although convective cooling is used, the air movement is not used to deliver humidity to the samples during exposure; rather, humidity is provided by floating the sample substrate in a water bath.

Further, as in the case of U.S. Pat. No. 4,817,477, the '954 patent uses artificial light sources for exposure of the samples.

U.S. Pat. No. 3,686,940 discloses a water-cooled cylindrical mirror, which rejects infrared radiation in an ultraviolet test apparatus. In the '940 patent, natural sunlight is not used.

U.S. Pat. No. 4,627,287 disclose a light resistance tester apparatus that eliminates nonuniformity of the temperature by providing a flow divider in the lower region of a sample-holder setting frame so that the circulating air can flow through the central part of the tester around the xenon lamp without contacting the surfaces of samples, thereby substantially eliminating the nonuniformity of temperature due to such circulating air.

A solar weathering device with control of sample temperature by cooling air is disclosed in U.S. Pat. No. 4,807,247. While this patent uses natural sunlight, a sample irradiance at accelerated levels of only up to 8 suns across the complete solar spectrum is employed.

U.S. Pat. No. 5,138,892 discloses accelerated light fastness testing of materials with xenon lamps and sample temperature control using airflow. Sample irradiance at accelerated UV levels of up to 8 suns (180 W/m<sup>2</sup> between 300–400 nm) are attainable. This patent does not utilize natural sunlight in its testing of materials.

A weather test machine using xenon lamps and sample temperature and humidity control using airflow is disclosed in U.S. Pat. No. 5,646,358. Uniform sample irradiance at accelerated levels up to 1–3 suns (within the UV bandwidth) is attainable. This patent does not utilize natural sunlight in its weather test machine.

U.S. Pat. No. 5,153,780 discloses a dish reflector and method for concentrating moderate solar flux uniformly on a target plane, said dish having stepped reflective surface characterized by a plurality of ring-like segments arranged about a common axis, each segment having a concave spherical configuration.

#### 3. The Need for Capabilities Beyond the Prior Art

There is a need for devising facilities for ultra-accelerated natural sunlight exposure testing of materials and devices under controlled weathering conditions that include several concurrent levels of temperature and/or relative humidity at very high levels of natural sunlight. This need is associated with the desirability to be able to predict the in-service lifetimes of said materials and devices from correlation's derived between such realistically accelerated test results and those obtained during normal use conditions. Further, there is a need to conduct these ultra-accelerated exposure tests at irradiance exposure factors of from about 25 to 100 suns, wherein the irradiance is highly uniform. The need to conduct these ultra-accelerated natural sunlight exposure tests of materials and devices should exclude artificial light sources which invariably introduce uncertainties regarding realistic spectral content of the irradiance stress on samples being exposed. For example, the use of artificial light leads to unrealistic degradation mechanisms and failure modes of exposed materials caused by low wavelength (<300 nm) photons that are not present in terrestrial solar spectra.

### SUMMARY OF THE INVENTION

In light of the drawbacks of the foregoing prior art, a general object of the present invention is to provide the unique capability to carry out ultra-accelerated exposure testing of materials and devices under controlled conditions

that include several concurrent levels of temperature and/or relative humidity at very high levels of natural sunlight, thereby permitting about a year's worth of representative weathering, in terms of natural sunlight exposure, to be accumulated in from about 3 to about 10 days.

A further object of the present invention is to provide ultra accelerated exposure testing of materials and devices by controlling sample temperatures and humidities and demonstrating that reciprocity relationships are obeyed (i.e., level of applied accelerated stress does not change failure/ degradation mechanism).

A yet further object of the present invention is to provide ultra-accelerated exposure testing of materials and devices that allows materials to be subjected to accelerated irradiance exposure factors of 25–100× to provide about a year's worth of representative weathering, in terms of natural sunlight exposure, to be accumulated in from about 3 to about 10 days.

A still further object of the invention is to provide a method of carrying out ultra-accelerated exposure testing of materials and devices utilizing a sample chamber that allows control of temperature and humidity during light exposure; wherein concentrated sunlight enters the chamber through an appropriate window, which may include quartz.

A further object yet still of the invention is to provide a method for carrying out ultra-accelerated exposure testing of materials and devices utilizing a cold mirror as a filter that reflects the ultraviolet/visible (UV/VIS) and transmits the near infrared (NIR) part of the solar spectrum, since the short wavelength (UV) light has been shown to be the predominant deleterious stress experienced by materials and devices during outdoor weathering.

Another object of the present invention is to provide a method of carrying out ultra-accelerated exposure testing of materials and devices under controlled weathering conditions, wherein conductive cooling of sample materials is provided by a water cooled substrate on to which samples are placed, and convective cooling is provided by blowing moist or dry air over the top surface of the samples, to provide high or low humidity to the samples during exposure of redirected concentrated sunlight into the exposure chamber to reduce the thermal load on the samples.

The invention is accomplished by the steps of: utilizing a solar concentrator to obtain elevated levels (25–100×) of concentrated sunlight with a uniform flux profile on the materials or samples being tested; splitting the solar spectrum into deleterious ultraviolet/visible (UV/VIS) light into the sample chamber; transmitting concentrated near-infrared (NIR) radiation to minimize undesirable thermal loading of material samples; and further control of temperature and/or relative humidity experienced by materials samples within the exposure chamber. The solar spectrum is split at a cut-off wavelength  $\lambda_{cutoff}$  such that UV/VIS consists of wavelengths less than  $\lambda_{cutoff}$  and VIS/NIR consists of wavelengths greater than  $\lambda_{cutoff}$ . Various combinations of concentrator designs (reflective and refractive), secondary reflectors, secondary concentrators, and turning mirrors can be used to provide the uniform flux. Additionally, the spectral splitting can be achieved at various points in the system through the use of coatings applied to any number of optical elements.

In terms of the best additional means for facilitating the general effect of ultra-accelerated natural sunlight exposure testing of materials, the facilities are as follows:

- 1) Multi-faceted concentrator design with facets having the following characteristics:  
Hexagonal, circular, rectangular, and triangular shaped facets arranged in a close packed array;

Facet centers located on a plane, parabola, sphere or other non-analytic shape;

Facet curvature that is flat, spherical, parabolic or aspheric; and

Facet reflector coatings designed to reflect UV light and transmit visible and IR, in the following configurations:

- a) Multi-faceted concentrator with geometry and design of facets to produce uniform flux on a sample chamber located at or near the aim point of the facets
  - b) Multi-faceted concentrator with secondary reflector designed to deliver uniform flux to the sample chamber located near the center of the facet array
  - c) Multi-faceted concentrator with secondary concentrator designed to deliver uniform flux to the sample chamber located near the exit of the secondary
  - d) Multi-faceted concentrator with secondary reflector designed to deliver uniform flux to the sample chamber located below the secondary to allow a horizontal orientation of the sample chamber.
  - e) Multi-faceted concentrator with secondary reflector designed to deliver uniform flux to the sample chamber located below a turning mirror placed near the center of the facet array.
  - f) Multi-faceted concentrator with secondary reflector designed to deliver uniform flux to the sample chamber below a turning mirror placed near the center of the facet array.
- 2) The multi-step concentrator of U.S. Pat. No. 5,153,780 "Method and Apparatus for Uniformly Concentrating Solar Flux for PV Applications using a reflector coating designed to reflect UV light and transmit VIS and NIR in the following configurations:
    - a) Multi-step concentrator with geometry and design of steps to produce uniform flux on a sample chamber located at or near the aim point of the various steps
    - b) Multi-step concentrator with secondary reflector designed to deliver uniform flux to the sample chamber located near the center of the multi-step concentrator
    - c) Multi-step concentrator with secondary concentrator designed to deliver uniform flux to the sample chamber located near the exit of the secondary
    - d) Multi-step concentrator with secondary reflector designed to deliver uniform flux to the sample chamber located below the secondary to allow a horizontal orientation of the sample chamber,
    - e) Multi-step concentrator with secondary reflector designed to deliver uniform flux to the sample chamber located below a turning mirror placed near the center of the multi-step concentrator
    - f) Multi-step concentrator with secondary reflector designed to deliver uniform flux to the sample chamber below a turning mirror placed near the center of the multi-step concentrator
  - 3) Fresnel lens concentrator/heat mirror configurations that only permit the desired spectral range to be transmitted:
    - a) with heat mirror positioned above the top surface of the lens
    - b) with one or both surfaces of the lens having a heat mirror coating
    - c) with heat mirror positioned between the lens and the sample



- d) with heat mirror positioned between the lens and sample, but oriented as a relay mirror to reflect the desired wavelengths to a position perpendicular to the plane of the lens
  - e) a two-stage Fresnel lens that interact as paired prisms to provide spectral selectivity
  - f) any of the above configurations combined with a secondary concentrator to achieve the desired flux uniformity
- 4) Holographic concentrator in the following configurations:
- a) achieves both spectral splitting and uniform concentration in its fundamental design
  - b) provides spectral splitting in its fundamental design and uses a secondary concentrator to achieve the uniform flux
  - c) concentrates in its fundamental design and uses a secondary concentrator to achieve the uniform flux, but with a cold mirror coating on the secondary
  - d) provides uniform flux in its fundamental design and uses a cold mirror to achieve the spectral splitting
  - e) concentrates in its fundamental design and uses a secondary concentrator to achieve the uniform flux, but with a cold mirror placed between the lens and secondary to achieve the spectral splitting
- 5) Use of a 2D or 3D micro lens array to achieve flux uniformity and/or spectral splitting
- 6) An array of Fresnel lens facets can be used to achieve flux uniformity and in conjunction with a heat mirror or a cold mirror can provide spectral splitting

#### BRIEF DESCRIPTION OF THE DRAWINGS

The drawings that are incorporated in and form part of the specification will illustrate alternative embodiments of the invention, and serve together with the description to explain the principles of the invention wherein:

FIG. 1 shows a multi-faceted concentrator design that receives incident natural sunlight. The design transmits VIS/NIR and reflects UV/VIS onto a sample exposure plane.

FIG. 2 shows a multi-faceted design that transmits VIS/NIR and reflects UV/VIS onto a secondary reflector, which in turn reflects uniformly concentrated natural sunlight onto a sample exposure plane.

FIG. 3 shows a multi-faceted concentrator design for affecting ultra-accelerated natural sunlight exposure testing, in which natural sunlight is made incident upon a multi-faceted design that transmits VIS/NIR and reflects UV/VIS through a secondary concentrator and onto a sample exposure plane.

FIG. 4 shows a multi-faceted concentrator design with a secondary reflector that delivers uniform flux to a sample chamber located below the secondary reflector to allow a horizontal orientation of the sample chamber.

FIG. 5 shows a multi-faceted concentrator with a secondary reflector designed to deliver uniform flux to a sample exposure plane in a chamber located below a turning mirror.

FIG. 6 shows a multi-faceted concentrator design that contains a reflector coating to reflect the full solar spectrum onto a secondary reflector that transmits VIS/NIR and reflects UV/VIS onto a sample exposure plane.

FIG. 7 shows a multi-faceted concentrator design that reflects the full solar spectrum onto a secondary reflector that in turn reflects only UV/VIS onto a horizontally disposed sample exposure plane.

FIG. 8 shows a multi-faceted concentrator design that reflects the full solar spectrum UV/VIS/NIR. The full solar spectrum is reflected onto a secondary reflector that transmits VIS/NIR and reflects UV/VIS onto a turning mirror that reflects the UV/VIS onto a horizontally disposed sample exposure plane.

FIG. 9 shows a multi-stepped concentrator design for uniformly concentrating solar flux, in which a plural-stepped concentrator having reflective surfaces is used to reflect UV/VIS onto a sample exposure plane and transmit VIS/NIR. Other combinations of elements can be used with the multi-stepped concentrator including a secondary reflector.

FIG. 9A shows a multi-stepped concentrator design for uniformly concentrating solar flux, in which a plural stepped concentrator having reflective surfaces is used to reflect UV/VIS onto a sample exposure plane and transmit VIS/NIR. Other combinations of elements can be used with the multi-stepped concentrator, including a turning mirror to allow repositioning of the sample exposure plane.

FIG. 10 shows a heat mirror positioned above the top surface of a Fresnel lens to allow only the desired spectral range to be transmitted and the Fresnel lens is used to uniformly concentrate the UV/VIS.

FIG. 11 shows another use of the Fresnel lens in which one or both surfaces of the Fresnel lens has a heat mirror coating that allows only the desired spectral range to be transmitted and the Fresnel lens is used to uniformly concentrate the UV/VIS.

FIG. 12 shows a Fresnel lens in which a heat mirror is positioned between the Fresnel lens and the sample plane to allow only the spectral range to be transmitted and the Fresnel lens is used to uniformly concentrate the UV/VIS.

FIG. 13 shows a Fresnel lens that provides uniform concentrated light on a sample exposure plane that is perpendicular to the plane of the Fresnel lens and uses a relay mirror that performs the desired spectral splitting and is positioned at an appropriate angle to achieve uniformity.

FIG. 14 shows a two-stage (double-layer) Fresnel lens arrangement in which the surface geometry is such that the desired concentrated uniformity over the required area in the sample exposure plane is achieved but the surface features of the two arrays (separated by low-index of refraction media such as air with  $n=1$ ) interact as paired prism elements to provide spectral selectivity.

FIG. 15 shows a refractive means by which the spatial splitting of wavelengths can be accomplished by using a pair of dispersion prisms to achieve spectral selectivity.

FIG. 16 takes any of the configurations described in FIGS. 10 to 14 above in which a secondary concentrator is incorporated to achieve the desired flux uniformity and/or to reposition the sample exposure plane to a more desirable orientation (i.e., horizontal) during exposure testing (where the secondary concentrator may also be used to perform spectral selectivity, as for example, functioning also as a cold mirror).

FIG. 17 shows a holographic device that concentrates the solar irradiance and performs the desired spectral splitting and provides flux uniformity over the required area in a sample exposure plane.

FIG. 18 shows a holographic device that concentrates the solar irradiance and performs the desired spectral splitting and uses a secondary concentrator to provide flux uniformity over the required area in a sample exposure plane (SEP).

FIG. 19 shows a holographic device that concentrates the solar irradiance and provides flux uniformity over the

required area in a sample exposure plane, and uses a cold mirror to achieve the desired spectral splitting.

FIG. 20 shows a holographic device that concentrates the solar irradiance and provides flux uniformity over the required area in a sample exposure plane, and uses a heat mirror to achieve the desired spectral splitting.

FIG. 21 shows a holographic device that concentrates the solar irradiance and uses a secondary concentrator to provide flux uniformity over the required area in a sample exposure plane and also uses the secondary concentrator to achieve the desired spectral splitting.

FIG. 22 shows a holographic device that concentrates the solar irradiance and uses a secondary concentrator to provide flux uniformity over the required area in a sample exposure plane and uses a heat mirror to achieve the desired spectral splitting.

FIG. 23 utilizes any of the configurations described in FIGS. 17–22 above, in which a secondary concentrator is incorporated to achieve the desired flux uniformity and/or to reposition the sample exposure plane to a more desirable orientation (e.g., horizontal) during exposure testing.

FIG. 24 shows as a means for refractively achieving concentrated solar irradiance and/or spectral splitting and/or flux uniformity with a 2-dimensional or 3-dimensional array of microlenses.

FIG. 25 shows a multi-faceted refractive element MFRE (i.e., lenses or Fresnel lenses) used in conjunction with a heat mirror.

FIG. 26 shows a cut-away view of an advanced exposure chamber design in accordance with the invention.

FIGS. 27a, 27b and 27c show additional views of the embodiment of the exposure chamber design of FIG. 26.

FIG. 28 is a perspective view of the system layout of the apparatus of the invention showing the sample chamber interface, via a cold mirror, with the HFSF/IRG components.

FIG. 29 shows the sample exposure chamber detail design that allows two levels of temperature and two levels of relative humidity to be maintained during sunlight exposure for the apparatus of the invention and ability to monitor spatial and spectral uniformity of the solar beam in situ during sample exposure; wherein:

FIG. 29a shows a top view of the heating/cooling chamber with samples in place.

FIG. 29b shows a top view of the chamber with humidity chamber in place.

FIG. 29c is a side view of the heating/cooling chamber.

FIG. 29d is a side view of the humidity chamber.

#### PREFERRED MEANS FOR FACILITATING ULTRA-ACCELERATED NATURAL SUNLIGHT EXPOSURE TESTING

Referring flow to FIG. 1, there is shown a multi-faceted concentrator design MF that receives incident natural sunlight NS. The multi-faceted design transmits VIS/NIR and reflects UV/VIS onto a sample exposure plane SEP in chamber means (not shown) that provide single or multiple concurrent levels of temperature and/or relative humidity to facilitate accelerated aging.

Natural sunlight NS is made incident on yet another multi-faceted MF design as shown in FIG. 2. In this figure, the multi-faceted design transmits VIS/NIR and reflects UV/VIS onto a secondary reflector SR, which in turn reflects uniformly concentrated natural sunlight onto the sample exposure plane SEP located in chamber means that provide

single or multiple concurrent levels of temperature and/or relative humidity to facilitate weathering of sample materials.

A multi-faceted concentrator design for affecting ultra-accelerated natural sunlight exposure testing is shown in FIG. 3 in which natural sunlight NS is made incident upon a multi-faceted design that transmits VIS/NIR and reflects UV/VIS through a secondary concentrator SC and onto a sample exposure plane SEP disposed within chamber means that provide single or multiple concurrent levels of temperature and/or relative humidity.

A multi-faceted concentrator MF design configuration with a secondary reflector SR designed to deliver uniform flux to a sample chamber located below the secondary reflector to allow a horizontal orientation of the sample chamber is shown in FIG. 4, in which natural sunlight NS is made incident upon the multi-faceted concentrator that transmits VIS/NIR and reflects UV/VIS onto the secondary reflector SR, which in turn, reflects a uniform flux of UV/VIS onto the horizontally disposed sample exposure plane SEP within chamber means that provide single or multiple concurrent levels of temperature and/or relative humidity.

A multi-faceted concentrator MF with a secondary reflector SR designed to deliver uniform flux to a sample exposure plane SEP in a chamber located below a turning mirror TM is shown in FIG. 5. In this figure, natural sunlight NS is made incident upon MF which transmits VIS/NIR and reflects UV/VIS onto secondary reflector SR which reflects a uniform flux onto a turning mirror TM, that in turn reflects UV/VIS onto a sample exposure plane SEP in chamber means that provide single or multiple concurrent levels of temperature and/or relative humidity to cause accelerated weathering.

A multi-faceted concentrator MF that contains a reflector coating to reflect the full solar spectrum is shown in FIG. 6. In FIG. 6 natural sunlight is made incident upon the multi-faceted reflector coating, and the full spectrum UV/VIS/NIR is reflected onto a secondary reflector SR, which transmits VIS/NIR and reflects UV/VIS onto a sample exposure plane SEP located in chamber means that provide single or multiple concurrent levels of temperature and/or relative humidity to facilitate accelerated aging of the test sample.

A multi-faceted concentrator design MF that reflects the full solar spectrum onto a secondary reflector SR that in turn reflects only UV/VIS onto a horizontally disposed sample exposure plane SEP is shown in FIG. 7.

FIG. 8 shows a multi-faceted concentrator design MF that also reflects the full solar spectrum UV/VIS/NIR. The UV/VIS/NIR is reflected onto a secondary reflector SR which transmits VIS/NIR and reflects UV/VIS onto a turning mirror TM that reflects the UV/VIS onto a horizontally disposed sample exposure plane SEP located in chamber means that provide concurrent levels of temperature and/or relative humidity to facilitate accelerated aging of the sample material.

In FIG. 9, a multi-stepped concentrator design for uniformly concentrating solar flux is shown, in which a plural-stepped concentrator dish 10 having reflective surfaces comprised of for example, 5 reflective surface elements, including a hub element designated by n1 and ring-shaped reflective elements n2–n5, lies symmetrically about a common axis A. The reflective elements n1–n5 are definable by reference dish RD, an imaginary parabolic dish that shares a common axis A, as shown. Reference dish RD has a focal length F and a target plane TP perpendicular to the A axis,

at a distance equal to the focal length  $F$  from the vertex  $V$ , and the sample exposure plane  $SEP$  located in chamber means that provide single or multiple concurrent levels of temperature and/or relative humidity to facilitate accelerated aging. The multi-step concentrator employs a reflector coating  $RC$  that reflects  $UV/VIS$  onto the  $SEP$  and transmits  $VIS/NIR$ .

Alternative design configurations to the multi-step concentrator with geometry and design of facets to produce uniform flux on a sample chamber located at or near the aim point of the facets (as shown in FIG. 9), can be: a multi-step concentrator with secondary reflector designed to deliver uniform flux to the sample chamber located near the center of the facet array; a multi-step concentrator with secondary concentrator designed to deliver uniform flux to the sample chamber located near the exit of the secondary concentrator; a multi-step concentrator with secondary reflector designed to deliver uniform flux to the sample chamber located below the secondary concentrator to allow a horizontal orientation of the sample chamber; and a multi-step concentrator with secondary reflector designed to deliver uniform flux to the sample chamber below a turning mirror placed near the center near the facet array.

Referring now to FIG. 10, it can be seen that uniform, non-concentrated natural sunlight  $NS$  is incident on a heat mirror  $HM$  which reflects  $VIS/NIR$  but transmits  $UV/VIS$ . The  $UV/VIS$  is transmitted to a Fresnel lens  $FL$  to permit only the desired spectral range of uniform concentrated spectrally split natural sunlight  $D$  to be incident upon the sample exposure plane  $SEP$ .

One or both of the surfaces of a Fresnel lens may be provided with a heat mirror coating  $HMC$  that allows the desired spectral range to be transmitted, as is shown in FIG. 11, where uniform, non-concentrated incident natural sunlight  $NS$  is made incident upon a heat mirror coating  $HMC$  on either the top or bottom or both sides of a Fresnel lens  $FL$ , so that  $UV/VIS$  is transmitted onto a sample exposure plane  $SEP$ .

Another of the preferred embodiments for facilitating ultra-accelerated natural sunlight exposure testing is by a heat mirror  $HM$  positioned between a Fresnel lens and the sample plane to permit only the desired spectral range to be transmitted, as is shown in FIG. 12. In FIG. 12, uniform, non-concentrated incident natural sunlight  $NS$  is made incident to a Fresnel lens  $FL$  which transmits a uniformly-concentrated, broad-band spectral range to a heat mirror  $HM$  that reflects  $VIS/NIR$ , but transmits  $UV/VIS$  onto a sample exposure plane  $SEP$ .

In a further preferred embodiment, as shown in FIG. 13, a Fresnel lens  $FL$  is designed to provide uniform non-concentrated incident sunlight  $NS$  and transmits the full spectral range onto a cold relay mirror, which in turn transmits  $VIS/NIR$  and reflects  $UV/VIS$  onto a sample exposure plane  $SEP$ .

In the preferred embodiment of FIG. 14, a 2-stage or double layer uniform concentrated  $UV/VIS$  Fresnel lens arrangement is used in which the surface geometry is such that not only is the desired concentrated uniformity over the required area in the sample exposure plane achieved but the surface features of the arrays (separated by a low-index of refraction media, such as air with  $n=1$ ) interacts as paired prism elements to provide spectral selectivity. In FIG. 14, uniform non-concentrated natural sunlight  $NS$  is made incident to a first Fresnel/prism array  $FLA 1$  so that the light is spatially separated into distinct wavelengths ("rainbow"). A masking pattern is then placed on to the top surface of a

second Fresnel prism array  $FLA 2$  to block unwanted wavelengths  $>\lambda_{cutoff}$  (i.e. high  $VIS$  and  $NIR$ ) such that the light exiting  $FLA 2$  is recombined light with a  $\lambda < \lambda_{cutoff}$  prior to directing the re-combined light with the  $\lambda < \lambda_{cutoff}$  onto a sample exposure plane  $SEP$ .

A pair of dispersion prisms (1 and 2) can be used to achieve spectral selectivity in the following manner, as shown by FIG. 15, in which there is first made an input of uniform distribution of the full solar spectrum  $FSS$  through a first prism to affect spatially separated/distinct wavelengths  $SSDW$  on the one hand and to cause adjustable stop blocks of transmitted wavelengths accelerated  $\lambda > \lambda_{UV/VIS}$  or  $\lambda > \lambda_{cutoff}$ , and in which prism No. 2 is used to re-construct or homogenize the spatially selected wavelengths from prism No. 1 to obtain an output uniform distribution of spectrally selected light  $UDSSL$  with  $\lambda < \lambda_{cutoff}$  which is then concentrated in a Fresnel lens-like manner. In this connection, it should be noted that the adjustable stop blocks can be directly applied to the first surface of prism No. 2 (as for example by the use of black paint).

In general, any of the configurations described in FIGS. 10–14, in which a secondary concentrator is incorporated to achieve the desired flux uniformity and/or to reposition the sample exposure plane to a more desirable orientation (i.e., horizontal) during exposure testing may be suitable and it should be noted that the secondary concentrator may also be used to perform the spectral selectivity, for example, so as to be able to function as a cold mirror as is shown in FIG. 16. In FIG. 16, uniform, non-concentrated natural sunlight  $NS$  is made incident upon a tracking primary Fresnel lens array  $FLA$ , and from which the transmissions are adjusted with a secondary concentrator  $SC$  that adjusts with primary tracking. The secondary concentrator transmits  $VIS/NIR$  (as is done with a cold mirror) where upon uniform concentrated  $UV/VIS$  is then reflected onto a fixed horizontal sample exposure plane  $SEP$ .

The specific embodiment of FIG. 17 shows a holographic device that concentrates the solar irradiance and performs the desired spectral splitting and provides flux uniformity over the required area in a sample exposure plane. More specifically, in FIG. 17, uniform, non-concentrated natural sunlight  $NS$  is made incident upon a holographic device  $HD$  which directs concentrated  $UV/VIS$  onto a sample exposure plane  $SEP$ , and the spectrally split  $VIS/NIR$  is made to miss the sample exposure plane.

In the preferred embodiment of FIG. 18, there is shown a holographic device that concentrates the solar irradiance and performs the desired spectral splitting and uses a secondary concentrator to provide flux uniformity over the required area in the sample exposure plane. More specifically, in FIG. 18, uniform non-concentrated natural sunlight  $NS$  is made incident upon a holographic device  $HD$ , which spectrally splits the incident light into a non-uniform concentrated  $UV/VIS$  input so that it falls on a secondary concentrator  $SC$  to provide a uniform concentrated  $UV/VIS$  output on the sample exposure plane  $SEP$ , and whereby the non-uniform concentrated  $VIS/NIR$  is split away from the secondary concentrator.

In yet another preferred embodiment, as shown in FIG. 19, a holographic device  $HD$  is used to direct uniform, non-concentrated natural sunlight  $NS$ , where upon the incident  $NS$  is directed through the  $HD$  to transmit  $VIS/NIR$  onto a cold mirror  $CM$  that reflects  $UV/VIS$  onto a sample exposure plane  $SEP$ .

A still further embodiment of the invention as is shown in FIG. 20, which utilizes a holographic device that concen-

trates the solar irradiance and provides flux uniformity over the required area in a sample exposure plane and utilizes a heat mirror to achieve the desired spectral splitting (UV+low-VIS versus high-VIS+NIR). In particular, the holographic device HD is utilized to direct uniform, non-concentrated natural sunlight NS through a heat mirror HM to effect spectral splitting so that, UV/VIS is transmitted onto a sample exposure plane SEP and the VIS/NIR is reflected off of the heat mirror.

A holographic device HD through which uniform, non-concentrated natural sunlight NS is directed is shown in FIG. 21. In the preferred embodiment of FIG. 21, the holographic device directs the incident NS so that transmitted VIS/NIR is passed through a secondary concentrator cold mirror SCCM and UV/VIS is reflected from the SCCM onto a sample exposure plane SEP.

In the specific embodiment shown in FIG. 22, a holographic device HD is utilized to direct uniform, non-concentrated natural sunlight NS onto a heat mirror HM that transmits concentrated non-uniform UV/VIS flux onto a secondary concentrator SC, which concentrates uniform UV/VIS flux onto a sample exposure plane SEP, while the heat mirror simultaneously reflects VIS/NIR.

Any of the facilities shown in the configurations of FIGS. 17–22, in which a secondary concentrator SC is incorporated to achieve the desired flux uniformity and/or reposition the sample exposure plane to a more desirable orientation (for example, horizontal) during operation can be used by adjusting the secondary concentrator with primary tracking, as is shown in the specific embodiment of FIG. 23. In FIG. 23, uniform non-concentrated natural sunlight NS is directed through a holographic device HD so that the UV/VIS portion of the NS is reflected off of a secondary concentrator SC (and the VIS/NIR portion is transmitted) that is adjusted with primary tracking so as to reflect uniformly concentrated natural sunlight onto a horizontal fixed sample plane HFSP. VIS/NIR is transmitted by the SC.

Another means for refractively achieving concentrated solar irradiance and/or spectral splitting and/or flux uniformity is with a 2-dimensional or 3-dimensional array of micro lenses. In this connection, reference is made to FIG. 24 in which such an array of micro lenses is shown in cross section. As can be seen in FIG. 24, a cross sections view of the 2-dimensional or 3-dimensional array of micro lenses in which the individual lenses IL is shown. A top view of the individual micro lenses is also shown.

Just as multi-faceted reflective elements can be used to achieve uniform concentration, multifaceted refractive elements (i.e., lenses or Fresnel lenses) can be used in conjunction with heat mirrors and/or cold mirrors and/or secondary concentrators, as is shown in FIG. 25. In FIG. 25, uniform, non-concentrated natural sunlight NS is directed through a multi-faceted array of lenses MFRE onto a heat mirror HM which transmits UV/VIS onto a sample exposure plane SEP and reflects VIS/NIR. This multi-faceted array of lenses may also be substituted for holographic devices shown in the embodiments of FIGS. 17–23, where heat and/or cold mirror coatings are applied to the lenses or separate elements or are incorporated into secondary concentrators.

FIG. 26 is a top view of an alternative embodiment of the exposure chamber design, showing a cut-away view. Samples 90 are disposed so that they are separated by a chamber divider 91. The chamber divider is in turn separated by an insulation divider 92. In this embodiment, larger heating/cooling ports 93 are disposed below the humidity ports 94.

As can be seen from the embodiment in FIG. 27, a number of alternative ways exist for improving the performance and ease of use of the sample exposure chamber. For example, baffles may be added with heating and cooling using a circulating bath with an approximate range of  $-20$  to  $100^{\circ}$  C., thereby eliminating the need for individual electric cartridge heaters that give rise to non-uniform sample exposure temperatures within a given quadrant. The baffles and chambers may be machined out of one solid block of aluminum and enlarged slightly. This would allow more room for thermocouple wires and insulation and also provide a better seal between chambers. In addition, an insulated, outside shell may be fabricated, that both chambers would rest in. This design configuration helps keep temperatures constant and makes the assembly solid.

FIG. 27 is a top view of FIG. 26 minus the samples. FIG. 27b is a view taken along the line A—A of FIG. 27a, showing the quartz cover plate 100, humidity chamber 101, the insulation 102, a heating/cooling chamber with baffles 103, fiber optic guides 104, and an insulated box 105, around the chambers.

FIG. 28 shows the cross-sectional system layout of the IRG 106, cold mirror 107 and sample chamber 108, wherein incident concentrated sunlight ICS is passed through the IRG and uniform sunlight US exits. An improved chamber was designed and fabricated that allows up to four replicate samples of about  $2.2\text{ cm} \times 2.2\text{ cm}$  square in size each to be exposed to the same high level of accelerated solar flux at two levels each of temperature and humidity. For example, at a given flux (e.g.,  $50\times$  suns), sets of samples can be simultaneously exposed at Tlow, RHlow, Tlow, RHhigh; Thigh, RHlow; and Thigh, RH high. This allows a fourfold increase in experimental throughput at a particular exposure flux.

A detailed drawing of the sample exposure chamber is shown in FIG. 29. FIG. 29a is a top view of the heating/cooling chamber with samples S in place, and showing heating/cooling parts HCP. FIG. 29b is a top view of the chamber with the humidity chamber in place. During testing the samples are mechanically attached to the top surface of the heating/cooling chamber to provide good thermal contact. The humidity chamber sits atop the heating/cooling chamber. FIG. 29c is a side view of the heating/cooling chamber, showing the pathway P for fiber optic probes and the cross section view of the heaters 109. FIG. 29d is a side view of the humidity chamber showing the humidity ports HP and the highly transmissive quartz window 110.

We claim:

1. An apparatus for providing ultra-accelerated natural sunlight exposure testing for sample materials under controlled weathering conditions comprise: means for concentrating solar flux uniformly as concentrated uniform reflected light; means for directing said concentrated uniform reflected light onto sample materials contained in a chamber having means to provide single or multiple concurrent levels of temperature and/or relative humidity, wherein said means for concentrating solar flux uniformly and means for directing concentrated uniform reflected light comprise:

- i) a multi-stepped concentrator that receives incident natural sunlight, transmits VIS/NIR and reflects a uniform flux of UV/VIS onto a vertically disposed sample exposure plane disposed in chamber means about a common axis of reflective elements of said multi-stepped concentrator to provide concurrent levels of temperature and/or relative humidity that allow sample materials to be subjected to accelerated irradiance

## 13

exposure factors for a significant period of time of about 3 to 10 days to provide a corresponding time of about at least a years worth of representative weathering of sample materials; said

multi-stepped concentrator utilizing a secondary reflector to reflect UV/VIS onto a sample exposure plane located near the center or below the center of the axis.

2. An apparatus for providing ultra-accelerated natural sunlight exposure testing for sample materials under controlled weathering conditions comprising: means for concentrating solar flux uniformly as concentrated uniform reflected light, and means for directing said concentrated uniform reflected light onto sample materials contained in a chamber having means to provide single or multiple concurrent levels of temperature and/or relative humidity, wherein said means for concentrating solar flux uniformly and means for directing concentrated uniform reflected light comprise:

## 14

i) a multi-stepped concentrator that receives incident natural sunlight, transmits VIS/NIR and reflects a uniform flux of UV/VIS onto a vertically disposed sample exposure plane disposed in chamber means about a common axis of reflective elements of said multi-stepped concentrator to provide concurrent levels of temperature and/or relative humidity that allow sample materials to be subjected to accelerated irradiance exposure factors for a significant period of time of about 3 to 10 days to provide a corresponding time of about at least a years worth of representative weathering of sample materials; said

multi-stepped concentrator utilizing a turning mirror to reflect UV/VIS onto a sample exposure plane located near the center or below the center of the axis.

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